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On the Effect of the Temperature of Liquid Hydrogen (-252$\cdot $ 8 $ ^{\circ} $ C.) on the Tensile Properties of Forty-One Specimens of Metals Comprising (a) Pure Iron 99 $\cdot $85%; (b) Four Carbon Steels; (c) Thirty Alloy Steels; (d) Copper and Nickel; (e) Four Non-Ferrous Alloys

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IX. *On the Effect of the Temperature of Liquid Hydrogen* (−252·8° *C.*) *on the Tensile Properties of Forty-one Specimens of Metals comprising* (a) *pure iron* 99·85%; (b) *four carbon steels;* (c) *thirty alloy steels;* (d) *copper and nickel;* (e) *four non-ferrous alloys.*

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[Plates 6 and 7.]

Contents.

1. *Introduction.*

The effect of low temperatures on the mechanical properties of metals, and specially of iron and steel, first received active attention many years ago. The earliest investigations were stimulated by the practical importance of this effect, which, it was known or suspected, was to embrittle ordinary iron and steel.

The first reports of any magnitude on the subject were those by the Canadian Dominion Board of Trade and the German Railways. Both of these reports appeared in 1871, and were mostly concerned with the possible dangers through iron and steel becoming brittle owing to the specially low natural temperatures occurring over large districts in those countries.

The practical importance of the behaviour of iron and steel at low temperatures has since increased with the development of refrigeration and the liquefaction of gases on a practical scale, also through the use of aircraft, which in the higher altitudes experience temperatures as low as — 50° C. or even still lower.

The subject is also of considerable interest from the purely scientific point of view. Much information has been accumulated regarding the effect on the mechanical and other properties of iron and steel at above room temperatures, the acquirement of which knowledge has in recent years been much stimulated by the increasing use of what are known as heat-resisting steels. Such knowledge cannot be regarded as complete without exploring the whole possible range of temperature.

Consider, for example, "the critical points" of steel. For many years the only such points known were the A_1, A_2, and A_3 points, and it was not until better facilities were available for experimentation at temperatures higher than 1,000° C. that a fourth point, A_4, was discovered, representing the inversion of A_3. Without this discovery our knowledge of the metallography of iron and ferrous alloys would be very incomplete, and the explanation of their properties in some cases badly understood.

On the other hand, referring to low temperatures, until the late Dr. J. HOPKINSON, F.R.S., demonstrated the fact, it was not known that certain nickel steels of high percentage, the non-magnetic properties of which appeared to indicate them as abnormal, were really quite normal. He was able to demonstrate that the critical point (Curie temperature) at which iron and most steels recover their magnetic state on cooling is, for these high nickel steels, below atmospheric temperature, although the reverse change on heating is, as ordinarily, above atmospheric temperature.

Broadly speaking, we know now that physical and chemical activity increase with temperature. High temperatures represent activity and instability, giving the manipulative power of man scope to mould Nature itself into useful channels. Low temperatures, on the other hand, represent stability, hardness, and sluggishness. It is not to be wondered at, therefore, that, apart from the readier facilities for producing high temperatures, a much greater amount of research has been carried out in the former field, and practical results and knowledge of considerable importance have been derived.

Nevertheless, researches at low temperatures have not been without most interesting discoveries, resulting in some important applications. Apart from the uses which this world, active as it is, has for the inactivity produced by cold, as in biological passivity caused by refrigeration, there is, for example, the phenomenon of supra-conduction discovered by Professor ONNES, *i.e.*, the possible complete annihilation of resistance to the flow of an electric current in lead, tin, and certain other metals. Who can say what may eventually be the practical outcome of such a discovery?

Thus the present research is an extension of the investigations already made in this field of low temperatures.

It is believed that this series of tests represents the first time that the metal iron and alloy steels have been mechanically tested at the low temperature of — 252·8° C.

2. Previous Researches at Temperatures Lower than—100° C.

Down to about the year 1900 it is believed that no systematic researches had been made on the mechanical properties of iron and steel below about — 100° C. At that time one of the authors (Hadfield) undertook an investigation into the mechanical and other physical properties of a series of irons, ordinary and alloy steels, at the temperature of liquid air (— 182° C.).

In the carrying out, at the Royal Institution, of the tensile tests on the material used in this research, by the kindness of the managers of that body, he also had the valuable collaboration of the late Sir James Dewar, F.R.S. The results were partly described in the joint paper by Dewar and Hadfield,* and the complete account was given in the special monograph by Hadfield.† This paper gives a very full description of the work and also contains some account with a complete bibliography of the work of earlier investigators. It is this paper, read before the Iron and Steel Institute, which is quoted in the present paper.

Tensile tests in liquid air were later carried out, again at the Royal Institution, on a series of nine iron-nickel-manganese-carbon alloys of varying nickel contents from 0 to 19·91% Ni. These alloys formed the subject of the Seventh Report (1905) by Carpenter, Hadfield, and Longmuir, to the Alloys Research Committee of the Institution of Mechanical Engineers, the results of the tensile tests in liquid air being shown in Table 12 of that report.

In 1920 the further progress made by which liquid hydrogen (— 252·8° C.) could be produced in sufficient quantities for experimental work, suggested to one of the authors (Hadfield) that the opportunity might be taken to settle a metallurgical question of interest. This concerned the existence or otherwise of transformations (critical points) in the higher percentage alloys of iron and manganese at temperatures even lower than that of liquid air. A further research was therefore carried out in collaboration with the late Professor Kamerlingh Onnes‡. The tests carried out even included a limited number in liquid helium (— 269°), only 4 degrees above the absolute zero. The question at issue was definitely settled by this work, the complete absence, at low temperatures, of any magnetic transformation in the iron-manganese alloys proving these to be quite different in their (metallurgical) constitution from the iron-nickel alloys, which do show such transformations.

3. The Present Research.

(a) Its Objects.

Briefly, it may be said that the research at the temperature of liquid air to which reference has already been made established the following principal facts.

* 'Proc. Roy. Soc.,' vol. 74, p. 326 (1904).

† 'J. Iron Steel Inst., No. 1,' p. 147 (1905).

‡ 'Proc. Roy. Soc.,' A, vol. 99, p. 174 (1921).

Iron becomes more brittle, and increases in tenacity, progressively down to the temperature of — 182° C. At this temperature its tenacity has risen from 25 to 52 tons per square inch, and the whole of the ductility has practically disappeared.

Unlike iron, somewhat singular to say, nickel, copper, and aluminium, although similarly increased in tenacity by the effect of low temperature and in much the same proportion as iron, not only suffered no loss of ductility, but, on the contrary, each showed an increase of ductility, which was particularly marked for aluminium. The elongation of this metal, was greatly increased in liquid air as compared with that at ordinary temperature.

In general, but with exceptions, alloys of iron with other elements, including carbon, behaved in the same way as iron itself, although the ratio of increase in tenacity, and the degree of the effect on their toughness, varied.

The effects of low temperatures are in general only temporary; that is, except in certain special cases to be referred to later, on return to normal temperature these materials are in no way better or worse for their having been subjected to cold. This shows that probably no change of structure has occurred.

The element having the most favourable influence in preventing iron becoming brittle at low temperature is undoubtedly nickel.

The same increase of tenacity occurs in nickel steels, and quite remarkable results can be obtained with them. With suitable proportions of nickel and carbon, contrary to the usual effect on brittleness of low temperatures, tensile properties are obtained showing a desirable combination of specially high tenacity with excellent ductility such as has not been obtained at ordinary temperatures.

Thus, in the report of the Alloys Research Committee referred to, a steel designated K containing 0·41% carbon, 0·96% manganese, and 19·91% nickel showed in liquid air not only the remarkably high tenacity of 157·2 tons per square inch, but a ductility of 15·5%.

The nickel steels of more or less high percentage, depending on their content of carbon, manganese, or other additional element, undergo a permanent transformation at low temperatures. This, however, does not destroy the beneficial effect of the nickel. The alloy K mentioned above was, in fact, such a steel, being non-magnetic before immersion in liquid air and strongly magnetic on return to normal temperatures. A similar remark applies to specimen 1449A, fig. 6, Plate 7, in the Hadfield research, containing 0·70% carbon, 0·82% manganese, and 31·4% nickel. This with a tenacity of 111 tons per square inch in liquid air had a ductility of 10%.

The transformation occurring in these high percentage nickel steels, however, has the effect of giving them a specially high tenacity in place of a comparatively low one. Thus the tenacity of the alloy K at ordinary temperature before immersion in liquid air was only 43·9 tons per square inch, and of the alloy 1449A only 41 tons.

Of the different ferrous alloys tested previously Hadfield (*loc. cit.*) representing 109 combinations of iron with nine different elements it was only those which contained a comparatively large nickel content which showed exceptional toughness in liquid air.

Most striking of all the former results was the behaviour of the iron-nickel alloys containing 5 or 6% of manganese and from 0·6 to 1·2% carbon. This range of alloys was previously known as exceptional for their remarkable ductility at ordinary temperature. The alloy with 24·30% nickel has a tenacity of 51 tons and an elongation of 60%. The specially noticeable point concerning the properties of this alloy at the temperature of liquid air is that this high ductility is actually increased, namely, from 60 to 67%. This range of alloys is not permanently transformed, the original tensile properties being restored unaltered on return to normal temperature, with no change in the specific magnetism or dimensions.

Finally, among the curious facts noted was that for all those alloys containing nickel, whose ductility was undiminished or even increased in liquid air, the reduction in area at the fracture was appreciably diminished, as an average by about 50%. Thus, while maintaining the extent of their total elongation before fracture, these alloys do so with a distinct change in behaviour; that is, through a more uniform extension along the length of the test specimen, and less localized in the neighbourhood where fracture occurs.

With these interesting facts on record regarding the behaviour of iron and ferrous alloys at a temperature of − 182° C., it was a natural desire to explore, when opportunity occurred, still lower down the temperature scale. With the larger supplies of liquid hydrogen (− 252·8°) now available, owing to the progress made at Leiden in the production and maintenance of specially low temperatures, it was considered practicable to carry out a series of tensile tests in this medium. This was duly arranged and the tests completed as now to be described. The possibility of employing liquid helium, with a further advance down the scale to − 269°, was considered. This would have reduced the remaining margin of 20° from absolute zero by 16°. This idea had, however, to be abandoned for the present owing to the greater difficulties of producing liquid helium, and the large quantities which would be required owing to the much greater rate of evaporation.

The objects of the present research may be described, briefly, as being, to follow further the changes already observed in the tensile properties of iron and its alloys at − 182° C.; that is, to some 70° lower temperature; also, to observe whether a regular progression occurs in these changes or whether, on the other hand, any critical change of behaviour happens, introducing new features into the tensile properties.

(*b*) *Apparatus.*

Tensile Tests.—The apparatus for these tests is illustrated in fig. 1, and was designed by one of us (DE HAAS) at the University of Leiden. It operates in such a manner that oil pressure exerted on a piston is transmitted by means of a long rod to the test specimen which is immersed in liquid hydrogen. It was necessary that the chamber in which the specimen was tested should be completely sealed against access of air. Further, as a Dewar vessel of glass was necessary as a container for the liquid hydrogen, the construction had to be made in such a way that the sudden shock on fracture of the specimen did not break the vessel.

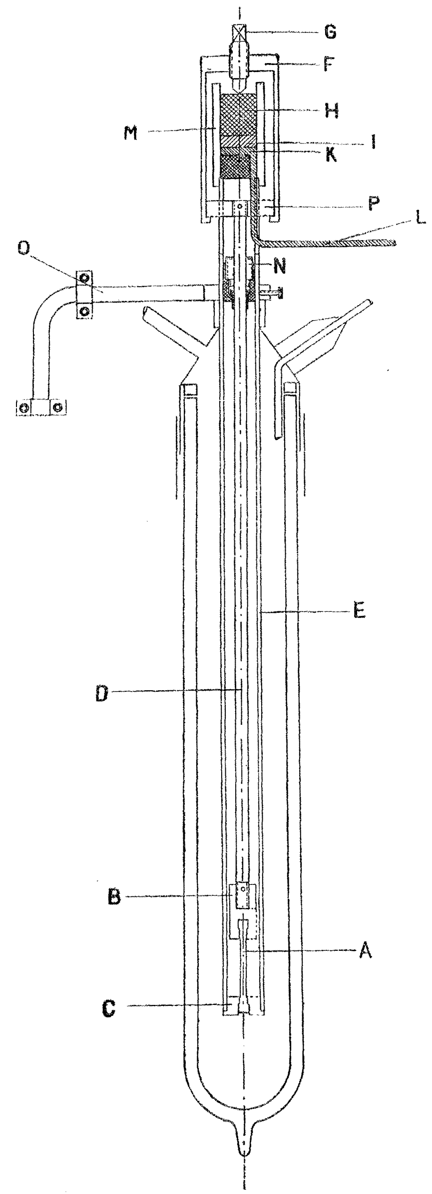

FIG. 1.—Apparatus for carrying out the tensile tests in liquid hydrogen.

Referring to fig 1, the construction is as follows: The bottom end of test specimen A is held in a disc C which closes the end of the long steel tube E. The specimen can readily be placed in position in the disc through a slot in the latter, which connects with the socket in which the end of the specimen rests.

At the upper end of the apparatus is the piston consisting of a copper block H, with leather packing I. This piston slides in the hollow cylinder M, which rests on the upper end of the tube E. The bottom end of M is closed, only a capillary tube L leading to the space K between the bottom of the cylinder and the piston.

The pressure on the piston is transmitted to the test specimen A via the screw G passing through the tube F, on the lower rim of which rests the winged nut P. This nut is screwed on to the steel rod D passing down inside the tube E and carrying at its lower end a holder B, into which the upper end of the test specimen A can be inserted by means of a slot.

In order to insert P into position, two slots are left free in the rim F. In the course of the test, P slides in two slots provided in the tube E.

When pressure is applied to the piston, it moves upwards, exerts its upward force on G, which transmits it to F, then to P, and finally through D to A.

To exclude air, the steel rod D moves through a stuffing box N which is vacuum tight.

The figure shows the arm O which carries the head of the cryostat, into which the vacuum vessel is fixed.

The load on A is determined by measuring the pressure exerted on H by means of a manometer and multiplying this by the cross-sectional area of H. The pressure is applied by means of a hand-driven oil compressor.

The tube E and rod D, forming the members which transmit the load to the specimen immersed in liquid hydrogen, were made from the special alloy steel known as AMF, which has a high content, about 50%, of nickel. This special steel is made by La Société Anonyme de Commentry-Fourchambault et Decazeville, Imphy, France, and, owing to its excellent toughness and strength at low temperatures, is much used for components in industrial plants for the liquefaction of gases. The tube of 20 mm. internal diameter was prepared by boring out a solid bar.

The form of the test specimen is shown with dimensions in fig. 2. This pattern with shoulders was adopted for ease of insertion into, and withdrawal from, the testing apparatus. The self-aligning spherical form of seating was used, as it was known that some of the specimens would be lacking in ductility, and any eccentricity of the load therefore specially liable to cause inaccurate results.

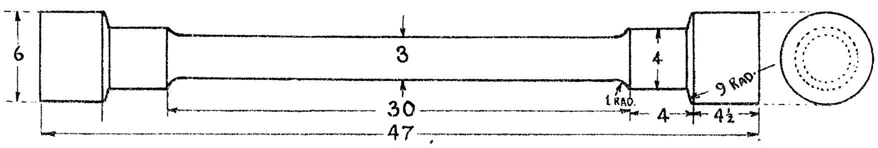

Fig. 2.—Dimensions of tensile test specimen in mm. Scale twice actual size.

In the operation of testing the specimen was allowed to attain the temperature of the liquid hydrogen before applying the stress, and remained immersed the whole time until fracture occurred.

Observation was made of the yield point in the usual way; that is, by a distinct retardation in the movement of the load gauge, where such occurred prior to the maximum stress; also of the maximum stress attained and the stress reckoned on the original cross-section at the moment of fracture. The data were completed by measurement of the elongation and reduction of area at fracture, on return to normal temperature, as described below.

The considerable number of specimens, 88 in all, made it worth while to construct at the Hadfield Research Department an auxiliary apparatus which proved most useful for measuring their elongation and reduction in section at fracture. This is shown in fig. 3, Plate 6, and was made by adding attachments to an existing measuring microscope.

The construction is such that the two parts of the test piece seen at A can be assembled in correct register with each other in the view of the microscope, and clamped firmly together during the measurements.

The elongation is obtained by focusing the microscope on one shoulder of the test-piece and travelling it along to the other. Part of this travel is made by sliding the microscope freely along the rods B between stops C, 3 cm. apart representing the original distance between the shoulders. The remainder of the travel is made by operating the screw micrometer head D, which thus measures directly the actual elongation of the specimen.

The reduced diameter at the fracture is measured on an internal scale in the microscope, which is of the type ordinarily used for measuring Brinell test impressions in a similar way. By turning the frame E holding the specimen through a right angle, a second measurement can be made and any ovality in the fracture thus taken account of.

Hardness tests.—The hardness determinations were made at the Hecla Works, Sheffield, on the ends of the tensile test specimens after they had been fractured. A small flat was prepared and polished for this purpose. The diamond pyramid test was employed under British standard conditions, using a load of 30 kg. The hardness figures so obtained have been converted to equivalent Brinell numbers by means of a calibration of the apparatus made for the purpose.

In addition to these directly determined hardness figures, taken at normal temperature, other hardness figures have, as previously mentioned, been deduced from the maximum stress obtained in the tensile tests made both at ordinary temperature and at $-252 \cdot 8°$.

(*c*) *Materials Tested.*

In all 41 materials have been tested, of which six are non-ferrous. Three of these materials, Nos. 3671, 1414A, and 1424B, have each been tested in two different physical conditions produced by varying the heat treatment.

In selecting the materials to be tested it was considered desirable to include those for which the properties at liquid air temperature had previously been ascertained HADFIELD (*loc. cit.*).

In all some 31 of these materials were included, making the selection as representative as possible, but with a preference for those which had retained some ductility in liquid air, specially the alloys containing nickel. These particular materials can be clearly identified in Tables I to V, from the fact that the results previously obtained in liquid air are shown for them.

The 10 remaining materials, of which four are non-ferrous, were selected from among the special alloys which have subsequently come into prominence. They will be described individually later in discussing the results obtained from them.

Heat Treatment.—The heat treatment applied in general to the ferrous specimens in the previous research was a double one, namely, a cooling in air from 1,102° C. following by a reheating to 777° and cooling slowly in the furnace. From the improved metallurgical knowledge obtained in the past 25 years it is now known that with forged or rolled specimens such as these a simple treatment consisting of slowly cooling from 800° is equally effective. This treatment was therefore adopted for those materials which had previously been given the double treatment. From an inspection of the corresponding results obtained on the specimens tested at ordinary temperature in the two researches it will be seen that for most of them the results obtained are quite similar, and the co-ordination of the results, therefore, is not seriously affected by this change in treatment.

Strictly, the temperature of the present single treatment should have been varied to allow for differences in the critical temperature of the various steels. This, however, would have entailed for some of the specimens further departure from the original treatment, and was not, therefore, thought advisable in the circumstances.

For materials which require a quite special treatment to develop their characteristics —as, for example, the Hadfield manganese steel—it was not necessary or desirable to modify the heat treatment primarily employed.*

(*d*) *Results.*

The test results have been brought together in Tables I to V, and are divided into groups as follows :—

Table I, Group I	.. ..	Irons.
Table II, Group II	..	Iron alloyed with one main element.
Table III, Group III	..	Iron alloyed with two main elements.
Table IV	Group IV (A) ..	Iron alloyed with three main elements.
	Group IV (B) ..	Iron alloyed with four main elements.
Table V, Group V	.. ..	Miscellaneous non-ferrous metals and alloys.

For convenience of reference, the classification of the specimens is the same as that adopted previously HADFIELD (*loc. cit.*). It was found necessary to include a new sub-group, IV (B), to accommodate the new material, 3731. This contains four special alloying elements, silicon, chromium, nickel, and tungsten; that is, apart from the ordinary ones, carbon and manganese.

(*e*) *Discussion of the Results.*

Effects on Ductility.—Considering the results first of all from the point of view of the effect of liquid hydrogen temperature on ductility, there are now available for 29 different materials their tensile characteristics both in liquid hydrogen and in liquid air.

The severity of the effect produced by liquid hydrogen is apparent in Table VI, only six of the 29 ferrous materials retaining any appreciable ductility. Among the remaining 23 which become brittle are the 11 materials which had previously shown little or no elongation in liquid air.

It will be noted that among this group is the metal iron itself, which therefore shows no return of its toughness on taking the temperature below − 182°.

* The whole of the various steels and steel alloys were prepared and produced at the Hadfield Works in Sheffield, where also the forging, heat treatment, and machining of the specimens were carried out.

The analyses of all the specimens, ferrous and non-ferrous, were also made at the Hadfield Research Laboratory.

TABLE

Group I.—

Specimen mark.	Analysis.							Tensile tests. Hadfield-Dewar (— 182° C.).				
									Normal temperature (+ 15° C.).		— 182° C.	
	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Class 1.—Swedish Charcoal Iron.												
S.C.1	0·04	0·07	Trace	—	—	—	99·82	As forged	23	25	52	Nil
2576	0·03	0·01	0·04	—	—	—	99·89	—	—	—	—	—

TABLE

Group II.—Iron alloyed

Class 1*a*.—Iron and Carbon, Low Manganese.												
1166A/4	0·14	0·08	0·07	—	—	—	—	1102° air 777° furnace	23	30	61	7½
1397 A.	0·37	0·38	0·20	—	—	—	—	Ditto	34	§ 20 R.A.63	66	17 R.A.39
1392 H.	0·78	0·10	0·10	—	—	—	—	Ditto	49 54	10 16	69	Nil
Class 1*b*.—Iron and Carbon, Higher Manganese.												
4147/104	0·24	0·59	1·04	—	—	—	—	1102° air 777° furnace	41	22	64	7½

† Fractured outside parallel portion of testpiece. ‡ Fractured in head of testpiece.

§ R.A.=Reduction of area.

I.

Irons.

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. Hadfield-Dewar. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	—252·8° C. Calculated.	Return to normal temperature. Actual.
As forged .	18·6	23·4	13·74	25·0	81·0	52·4	52·4	Nil	Nil	101 —	122 —	230 —	—	103	104	232	106

In Tables I to V at — 252·8° the stress at fracture was the same as the maximum stress (M.S.).

II.

with One Main Element.

800° furnace	19·05	21·4	17·25	27·5	77·5	69·2	69·2	0·3	2·5	101	—	281	—	95	114	326	105
} Ditto	—	—	—	—	—	67·2 67·5	67·2 67·5	Nil Nil	Nil‡ Nil‡	150	162	310	294	—	157	316 317	155 160
Ditto	42·4	44·1	41·3	12·0	35·0	54·8	54·8	0·2	Nil†	215 240	—	325	—	194	163	244	167
800° furnace	36·25	37·9	32·1	21·5	57·5	63·7	63·7	0·3	Nil†	180	—	300	—	167	186	298	178

* Calc. = deduced from tensile test.

TABLE II

Specimen mark.	Analysis.							Tensile tests. Hadfield-Dewar (— 182° C.).				
									Normal temperature (+ 15° C.).		— 182° C.	
	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Class 3.—Iron and Aluminium.												
1167 D	0·17	0·10	0·18	—	—	Al. 0·85	—	1102° air 777° furnace	28	25	56	12
Class 4.—Iron and Tungsten.												
1294 I.	0·38	0·11	0·20	—	—	W. 7·47	—	1102° air 777° furnace	52	12	79	7
Class 6.—Iron and Copper.												
1263 C.	0·17	0·15	1·04	—	—	Cu. 2·87	—	1102° air 777° furnace	34	20	67	2½
Class 7.—Iron and Nickel.												
1397 B.	0·26	0·33	0·18	—	0·58	—	—	1102° air 777° furnace	33 34	25 24	64	15
1287 D.	0·14	0·21	0·72	—	1·92	—	—	Ditto	34	20	59	12
1287 L.	0·16	0·30	1·0	—	24·51	—	—	1102° air 777° furnace 614° ,,	90	12	118	10
1449 A.	0·70	—	0·82	—	31·4	—	—	Ditto	41	30	111	10
3450	0·16	0·08	0·86	—	35·80	—	—	Not	includ	ed.		
5277	0·34	0·14	1·31	—	57·5	—	—	Not	includ	ed.		

† Fractured outside parallel portion of testpiece. ‡ Fractured in head of testpiece.

(continued).

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. Hadfield-Dewar. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	— 252·8°C. Calculated.	Return to normal temperature. Actual.
800° furnace	30·0	30·0	23·1	18·5	66·5	61·0	61·0	0·1	2·0	123	—	250	—	132	137	281	131
800° furnace	40·97	53·1	46·2	11·5	42·5	104·0	104·0	0·9	Nil†	230	—	375	—	235	228	464	230
800° furnace	36·2	41·7	—	16·5	55·5	77·5	77·5	0·8	Nil†	150	—	315	—	183	185	368	185
800° furnace	31·71	38·63	—	19·5	62·0	78·9	78·9	§	§	{ 145 150 }	—	300	—	169	159	375	154
Ditto	—	—	—	—	—	{ 53·1 54·1	53·1 54·1	Nil Nil	Nil‡ Nil†	} 150	—	269	—	—	170 {	235 240	168 180
Ditto	75·8	75·8	66·2	15·0	53·0	—	122·4	8·0	36·0	417	306	512	524	359	320	527	330
Ditto	30·0	43·11	—	29·0	45·5	96·5	118·5	11·0	16·5	180	—	487	—	189	162	513	317
1050° water	23·4	36·2	29·3	32·0	57·5	56·8	64·4	20·5	59·5	—	—	—	—	159	150	302	149
As forged	32·3	47·9	—	31·5	59·5	47·8	73·3	35·5	54·0	—	—	—	—	209	177	346	187

* Calc. = deduced from tensile test.

§ Half testpiece only available.

TABLE II

Specimen mark.	Analysis. C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Tensile tests. Hadfield-Dewar (— 182° C.). Normal temperature (+ 15° C.). Maximum stress. tons/sq. in.	Elongation. %	— 182° C. Maximum stress. tons/sq. in.	Elongation. %
Class 8*a*.—Iron and Manganese, Low Carbon.												
1379D./2	0·15	—	15·27	—	—	—	—	1048° water	39	5	46	2½
Class 8*b*.—Iron and Manganese, Higher Carbon.												
1010	1·23	—	12·64	—	—	—	—	1048° water	56	30	61	2½
1010	1·27	0·12	12·69	—	—	—	—	—	—	—	—	—

TABLE

Group III.—Iron alloyed

Specimen mark.	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Normal max. stress	Elongation	— 182° C. max. stress	Elongation
Class 1.—Iron, Nickel, and Copper.												
1252 B.	0·18	0·33	1·10	—	5·81	Cu 2·87	—	1102° air, 777° furnace	77	Nil	85	Nil
Class 2.—Iron, Nickel, and Chromium.												
1286 A.	0·25	0·26	0·40	0·64	2·67	—	—	1102° air, 777° furnace	38	20 R.A.62	61	17 R.A.21
3671	0·35	0·18	0·56 S.·009	0·71 P.·010	3·34	—	—	Not	includ	ed.		
3671	0·35	0·18	0·56 S.·009	0·71 P.·010	3·34	—	—	Not	includ	ed.		
3754	0·12	0·43	0·24	18·8	8·1	—	—	Not	includ	ed.		
Class 3.—Iron, Nickel, and Silicon.												
1103 A.	0·38	2·07	0·54	—	3·30	—	—	1102° air, 777° furnace	57	17	72	Nil

† Fractured outside parallel portion of testpiece.

(continued).

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. HADFIELD-DEWAR. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	—252·8° C. Calculated.	Return to normal temperature. Actual.
1050° water	42·39	42·39	42·39	5·5	Nil†	51·4	51·4	0·7	Nil†	172	—	200	—	188	278	227	279
— 1000° water	— 34·5	— 66·2	— 66·2	— 44·5	— 39·0	— 65·1	— 65·1	— Nil	— Nil†	250 —	198 —	281 —	364 —	— 311	— 227	— 305	— 245

III.

with Two Main Elements.

Treatment.	Yield point (normal)	Maximum stress (normal)	Stress at fracture	Elongation (normal)	Reduction of area (normal)	Yield point (—252·8°)	Maximum stress (—252·8°)	Elongation (—252·8°)	Reduction of area (—252·8°)	H-D Normal Calculated	H-D Normal Actual	H-D —182° Calculated	H-D —182° Actual	Present Normal Calculated	Present Normal Actual	—252·8° Calculated	Return Actual
800° furnace	73·03	83·35	83·35	7·5	11·5	55·8	55·8	Nil	Nil	365	—	396	—	390	344	249	352
800° furnace	31·0	35·5	27·6	21·0	59·0	53·1	53·1	Nil	Nil†	163	—	281	—	156	159	235	164
850° oil } 650° water }	59·3	65·1	—	13·5	59·5	108·5	108·5	4·5	48·5	—	—	—	—	305	284	479	280
850° oil } 300° water }	106·1	108·8	—	6·0	53·5	132·6	146·4	0·9	Nil†	—	—	—	—	480	466	605	457
1150° water	25·9	52·4	—	56·0	53·5	55·8	119·8	25·0	30·5	—	—	—	—	232	176	516	170
800° furnace	49·0	58·9	—	14·5	50·5	66·2	66·2	Nil	Nil†	256	—	340	—	269	248	311	248

* Calc. = deduced from tensile test.

TABLE III

Specimen mark.	Analysis. C.	Si.	Mn.	Cr.	Ni.			Tensile tests. Hadfield-Dewar (— 182° C.). Treatment.	Normal temperature (+ 15° C.). Maximum stress. tons/sq. in.	Normal temperature (+ 15° C.). Elongation. %	— 182° C. Maximum stress. tons/sq. in.	— 182° C. Elongation. %
Class 4.—Iron, Nickel, and Manganese.												
1109 D.	0·60	0·84	5·04	—	14·55	—	—	1048° water	59 57	70 52	72	25
1414 A.	1·0	—	6·05	—	17·91	—	—	—	—	—	—	—
1414 A.	1·0	—	6·05	—	17·91	—	—	1048° water	49	57	75	42
1414 B.	1·18	—	6·05	—	24·3	—	—	Ditto	51	60 R.A.62	84	67 R.A.47
Class 7.—Iron, Manganese, and Silicon.												
601	0·40	4·27	1·90	—	—	—	—	1102° air 777° furnace	66	2½	79	Nil
Class 8.—Iron, Manganese, and Copper.												
1240/1	0·25	0·31	2·01	—	—	Cu. 1·45	—	1102° air 777° furnace	44	§ 17 R.A.62	70	17 R.A.39
Class 9.—Iron, Chromium, and Aluminium.												
1179 B.	0·46	0·34	0·18	3·57	—	Al. 1·06	—	1102° air 777° furnace	56	10	75	5
Class 10.—Iron, Chromium, and Silicon.												
1185 F.	0·54	2·20	0·22	3·50	—	—	—	1102° air 777° furnace	61	15	70	Nil

† Fractured outside parallel portion of testpiece. ‡ Fractured in head of testpiece.

(continued).

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. HADFIELD-DEWAR. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	—252·8° C. Calculated.	Return to normal temperature. Actual.
1050° water	47·5	50·0	50·0	62·0	51·0	65·2	73·8	8·5	19·0	{269 256}	165	340	254	220	177	349	171
800° furnace	47·5	51·0	51·0	39·5	42·5	70·9	70·9	4·5	13·0	—	—	—	—	225	187	335	182
1050° water	22·7	51·0	—	51·0	64·0	67·2	78·2	13·0	25·5	215	—	355	—	225	159	376	153
} Ditto	25·9	54·8	53·4	51·0	59·5	81·0	86·8	26·0	50·5	225	173	392	286	244	191	404	182
800° furnace	55·5	55·5	55·5	1·0	Nil†	33·8	33·8	1·5	Nil†	310	—	375	—	248	266	149	270
}800°furnace	—	—	—	—	—	{74·5 80·3	74·5 80·3	Nil 0·3	Nil‡ 2·0	}193	—	330	—	—	208{	353 380	216 209
800° furnace	48·2	52·4	—	13·5	48·5	51·0	51·0	2·0	Nil†	250	—	355	—	232	214	225	215
800° furnace	51·65	63·05	—	16·0	43·5	61·4	61·4	0·4	Nil	281	—	330	—	294	272	283	269

* Calc. = deduced from tensile test. § R.A. = Reduction of area.

TABLE III

Specimen mark.	Analysis.							Tensile tests. Hadfield-Dewar (— 182° C.).				
									Normal temperature (+ 15° C.).		— 182° C.	
	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Class 11.—Iron, Chromium, and Copper.												
1255 A.	0·85	0·31	0·50	5·79	—	Cu. 1·83	—	1102° air, 777° furnace	62	12	77	Nil
Class 12.—Iron, Chromium, and Tungsten.												
1189 B.†	0·26	0·05	0·25	0·66	—	W. 1·99	—	1102° air, 777° furnace	41	17	67	5

TABLE

Group IV*A*.—Iron alloyed

Specimen mark.	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Class 1.—Iron, Cobalt, Manganese, and Silicon.												
1209 C.	0·25	0·64	1·04	—	—	Co. 1·8	—	1102° air, 777° furnace	34	22	57	12
Class 2.—Iron, Nickel, Manganese, and Copper.												
1424 B.	0·83	—	5·9	—	14·44	Cu. 2·25	—	—	—	—	—	—
1424 B.	0·83	—	5·9	—	14·44	2·25	—	1048° water	49	50	74	40
Class 3.—Iron, Chromium, Manganese, and Silicon.												
608	1·32	1·50	4·23	2·02	—	—	—	1102° air, 777° furnace	61	Nil	72	Nil
Class 5.—Iron, Manganese, Chromium, and Nickel. (*This Class not included in the*												
2339 C.	0·46	0·21	2·41	14·40	59·3	—	—	Not	includ	ed.		

† Fractured outside parallel portion of testpiece.

(continued).

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. Hadfield-Dewar. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	—252·8° C. Calculated.	Return to normal temperature. Actual.
800° furnace	55·8	59·9	59·9	10·0	35·5	46·2	46·2	0·3	Nil†	287	—	365	—	275	262	201	263
800° furnace	30·63	40·69	—	18·0	60·0	55·2	55·2	1·0	Nil†	180	—	315	—	179	174	246	170
IV. with Three Main Elements.																	
800° furnace	38·6	38·6	36·2	19·5	52·5	57·8	57·8	Nil	Nil†	150	—	256	—	170	166	260	164
800° furnace	49·2	52·4	47·5	44·0	60·0	73·7	73·7	2·5	8·5	—	—	—	—	232	196	348	209
1050° water	27·6	52·4	—	54·0	66·0	67·2	76·8	11·5	10·5	215	—	350	—	232	174	364	162
800° furnace	54·8	54·8	54·8	2·5	Nil†	42·7	42·7	Nil	Nil†	281	—	340	—	244	363	188	361
HADFIELD-DEWAR *Research.*)																	
As forged	50·3	54·4	—	22·0	58·0	60·3	77·6	28·5	40·5	—	—	—	—	242	230	368	212

* Calc. = deduced from tensile test.

TABLE IV

Specimen mark.	Analysis.							Tensile tests. Hadfield-Dewar (— 182° C.).				
									Normal temperature (+ 15° C.).		— 182° C.	
	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Group IVB.—Iron alloyed with Four Main Elements												
Class 1.—Iron, Chromium, Nickel, Silicon, and Tungsten.												
3731	0·44	1·62	1·34	14·60	27·3	W. 3·5	—	Not	includ	ed.		

TABLE

Group V.—Non-Ferrous

Specimen mark.	C.	Si.	Mn.	Cr.	Ni.		Fe.	Treatment.	Maximum stress. tons/sq. in.	Elongation. %	Maximum stress. tons/sq. in.	Elongation. %
Nickel. 1466 . .	0·09	Tr.	0·11	—	Ni. 99·27	Cu. 0·20	Fe. 0·28	As received	29	43	46	51
2908 . .	0·07	—	0·38	—	99·4	—	—	—	—	—	—	—
Copper. Driving band	—	—	—	Pb. 0·055	Sn. 0·46	Cu. 99·6	Fe. Tr.	Heated to dull red and cooled in air	15	42	23	45
Electrolytic	—	—	—	—	—	99·7	—	—	—	—	—	—
Monel metal	—	—	—	—	Ni. 67·0	Cu. 30·2	—	—	—	—	—	—
3542 . .	0·31	0·20	1·41	Cr. 18·9	Ni. 78·9	—	—	—	—	—	—	—
Phosphor-bronze. 6073 A.	—	—	—	—	Sn. 10·0	Cu. 88·38	Zn. 1·61	—	—	—	—	—
Duralumin. 6074/2	—	—	0·75	Mg. 0·57	Al. 94·0 apprx.	Cu. 4·1	Fe. 0·42	—	—	—	—	—

(continued).

Treatment.	Tensile tests. Present research (— 252·8° C.). Normal temperature. Yield point. tons/sq. in.	Maximum stress tons/sq. in.	Stress at fracture.	Elongation. %	Reduction of area. %	— 252·8° C. Yield point. tons/sq. in.	Maximum stress. tons/sq. in.	Elongation. %	Reduction of area. %	Brinell hardness tests. HADFIELD-DEWAR. Normal temperature. Calculated.*	Actual.	— 182° C. Calculated.	Actual.	Present research. Normal temperature. Calculated.	Actual.	—252·8°C. Calculated.	Return to normal temperature. Actual.
(This Group not included in the HADFIELD-DEWAR *Research.)*																	
1000° water	55·2	55·2	50·0	24·5	41·5	71·0	83·7	25·0	35·0	—	—	—	—	246	232	392	232
V. Metals and Alloys.																	
—	—	—	—	—	—	—	—	—	—	127	—	200	—	—	—	—	—
As forged	40·7	46·9	—	11·5	71·0	52·4	64·4	21·5	64·0	—	—	—	—	205	208	302	218
—	—	—	—	—	—	—	—	—	—	66	—	101	—	—	—	—	—
750° water	12·0	17·3	12·0	37·5	77·0	13·7	29·7	60·0	75·0	—	—	—	—	76	63	130	59
As forged	21·4	38·6	—	36·0	74·5	43·0	63·4	38·5	61·0	—	—	—	—	170	145	297	144
1000° water	46·2	59·3	—	27·5	51·5	62·0	84·1	34·5	50·0	—	—	—	—	271	236	393	222
As received (cast)	13·1	20·3	20·3	30·0	36·0	20·7	25·9	18·0	38·5	—	—	—	—	90	90	114	89
As rolled	22·4	30·0	27·6	18·0	33·5	35·1	45·8	17·0	20·0	—	—	—	—	132	135	199	132

* Calc. = deduced from tensile test.

TABLE VI.—Statistical results from 29 ferrous materials tested both in liquid air and liquid hydrogen.

Number of materials tested.	Elongation % in	
	Liquid air.	Liquid hydrogen.
11	Less than $2\frac{1}{2}$	2 or less (11 and 12)
12	5 to 17	
6	10 to 40	8 to 26
Total ... 29		

The remaining 12 materials which have proved brittle in liquid hydrogen had possessed in liquid air a ductility of from 5 to 17%. There remain of these 29 ferrous materials tested in both researches six, which even at the low temperature of $-252\cdot8°$ still retain a ductility of from 8 to 26%. Of these only two, namely, 1287L and 1449A, have not suffered an appreciable reduction by this further drop in temperature; these are the plain high percentage nickel steels. 1287L, with 24·51% nickel, has at $-252\cdot8°$ an elongation of 8·0%, comparing with 10% at $-182°$; for 1449A, with 31·4% nickel, the corresponding figures are 11·0 and 10% respectively.

1287L remains, in fact, remarkably little affected over the whole range from ordinary temperature down to $-252\cdot8°$, since at ordinary temperature its elongation was from 12 to 15%. 1449A, with the still higher nickel percentage, is, however, less tough at these low temperatures than at ordinary temperatures, where its ductility was 29 to 30%.

It is further interesting to note that this group—that is, the six ferrous materials which retain appreciable toughness in liquid hydrogen—includes the interesting alloys containing 5 to 6% of manganese with a comparatively high content of about 14 to 24% of nickel.

Because of their remarkable behaviour in liquid air there was reason to look for interesting results from them in the present tests. Although they still retain considerable ductility, anticipations were somewhat disappointed, specially for 1414B with 24·3% nickel. This alloy in liquid air had slightly improved in its ductility to a figure of no less than 67%, and a further increase in liquid hydrogen might reasonably have been looked for. Its actual ductility has, however, proved to be only 25%, compared with 51% obtained at ordinary temperature, so that in liquid hydrogen its normal ductility is now reduced by half.

In specimen 1414A, containing a rather less nickel content, 18%, the loss of ductility in liquid hydrogen to a figure of 13% is again greater than might have been anticipated, in view of the comparatively small loss between ordinary temperature and liquid air, namely, from 57 to 42%. Similar remarks apply to 1109D and 1424B, which are in this series, but which have still less nickel ($14\frac{1}{2}$%), 1424B having an addition also of $2\frac{1}{4}$% copper.

With the further lowering of the temperature to $-252 \cdot 8°$ two other ferrous alloys among those tested have, as shown later, now displaced 1414B from its position as the material with the greatest ductility. Nevertheless, in this further extension of the range of conditions under which this alloy of iron with nickel and manganese has been tested, it can be said to have still retained to a large degree its remarkable toughness.

Continuing with the materials which have been tested both in liquid hydrogen and in liquid air there remain the two non-ferrous metals, nickel and copper. Both these metals had by exposure to liquid air shown an improvement in their ductility, already high at ordinary temperature. With copper the ductility has still further increased from 45% to no less than 60% in liquid hydrogen.

The result is not quite so clear with nickel, because the new specimen, which it was necessary to use owing to none of the original material being available, is appreciably different in its tenacity at ordinary temperature. The new material now tested has a tenacity of 47 tons per square inch, as compared with 29 tons for the material used in the Hadfield research, and its ductility is correspondingly less—11·5 as against 43%. Since, however, this ductility of 11·5% is increased in liquid hydrogen to 21·5%, or nearly doubled, while that of the original specimen in liquid air was only increased from 43 to 51%, it may reasonably be concluded that, as with copper, lowering the temperature has a progressively favourable influence on the ductility of nickel, even down to $-252 \cdot 8°$.

The high tenacity of the specimen of nickel used in the present research is certainly rather surprising, but it is confirmed by the Brinell hardness, and the identity of the test pieces has been checked chemically. No observation was made of the temperature of forging of the rod from which the test piece was turned, and it seems probable that this temperature must have been rather low, with an appreciable amount, therefore, of "cold work," and consequent mechanical hardening.

Turning to the materials used in the present research, which were not included in the Hadfield series of tests in liquid air, these are 11 in number, 7 containing iron in considerable proportion.

The results from the plain nickel-iron alloys 3450 and 5277, containing high percentages, 35·8 and 57·5, of nickel, demonstrate that as the percentage of nickel increases the ductility in liquid hydrogen also increases, until at 57·5% nickel it is actually greater at this low temperature than at ordinary temperature. Among the ferrous materials tested, this alloy 5277 has, in fact, the greatest ductility, 35·5%, of any. Since, associated with this excellent ductility, it has a tenacity as high as 73 tons per square inch, the choice of this material for the stressed members of the testing apparatus used in the present research will be seen to have been an excellent one.

It is evident that as the nickel percentage increases in these high-nickel alloys they partake more and more of the character of nickel itself, which, as has been seen, also improves in ductility by cooling to low temperatures, and to an even greater extent than this alloy, No. 5277.

Another of the alloys specially introduced for this research is No. 3754, with 18·8% chromium and 8·1% nickel. This represents the type of non-rusting and acid-resisting steel now in most general use, and familiarly known as 18 : 8. Its elongation at ordinary temperature is specially high, namely, 56%, and at the lower temperature the figure remains of quite respectable magnitude, 25%. Associated as this is with a tenacity of no less than 119·8 tons, a combination of high tenacity with excellent ductility, it presents, in fact, the best result obtained in this research.

Specimen No. 3671, with 0·71% chromium and 3·34% nickel, was introduced as representing a type of high-tenacity steel in general use in the automobile and aircraft industry. Previous experience HADFIELD (*loc. cit.*) had indicated that steels with contents of nickel and chromium of this same order retained in liquid air much of their original ductility, and to an extent rather better than similar nickel steels without chromium. This is a point of some importance in view of the use of aircraft in the upper and cold regions of the atmosphere, where brittleness in highly stressed members would be dangerous. This practical consideration did not, of course, demand investigation at such a low temperature as that of liquid hydrogen, which was made more for its scientific interest.

Steel No. 3671, it will be noted, is specially pure as regards its sulphur and phosphorus contents. It has been tested in two different physical conditions, representing high and low tenacities in the range obtainable by suitably varying the tempering temperature after quenching. The results show that under the very severe cooling in liquid hydrogen the ductility of this steel is adversely affected and in a marked way. With the steel originally in its condition of lowest tenacity and highest ductility (13·8%) the elongation retained in liquid hydrogen certainly reaches the moderate figure of 4·5%. In the high tenacity (109 tons per square inch) condition the original ductility of 6% is, however, almost entirely destroyed.

Specimen 3731 is representative of the material known as "Era/ATV" steel, which has been remarkably successful, on account of its heat-resisting properties, in its use for the exhaust valves of aeroplanes and motor cars, where these are subject to specially high duty. Another successful application is for the rotors of the exhaust turbines used for boosting the supply of air to the motors of aeroplanes at very high altitudes. These rotors, which are made in one piece, have, naturally, to be subjected at one and the same time to the high temperatures of 850° and 900° of the exhaust gases at one end, and at the other to the very low temperatures, − 50° C. or less, of the atmosphere at these high altitudes. It was of interest, therefore, to examine the characteristics of the steel at low as well as at the high temperatures at which its behaviour has been thoroughly explored. The results show that although its tenacity has, following the general rule, been increased by the very low temperature, from 55 to 84 tons per square inch, its excellent ductility of 24·5% has in no way suffered.

The suitability of this special steel for its application in exhaust turbine rotors of this type is therefore amply demonstrated.

The remaining alloy, No. 2339C, among the ferrous specimens actually contains only about 23% of iron. Nickel 59·3% is the preponderating element, with chromium also included to the amount of 14·40%. This alloy is representative of a material much used for electrical heaters, owing to its high electrical resistance and non-scaling properties when under heat. It is not surprising to find, in view of its high nickel content, that this alloy is improved in its ductility from 22 to 28·5% by cooling in liquid hydrogen. Compared with specimen 5277, which was a plain nickel-iron alloy of similar percentage, the chromium in 2339C seems to have had very little influence on the behaviour at low temperatures. 2339C, already at ordinary temperatures rather higher in tenacity and lower in ductility than 5277, retains the same relative characteristics in liquid hydrogen.

Finally, in studying the results from the point of view of ductility there remain the non-ferrous alloys introduced specially for this research. These are Monel metal, 3542, 6073A (phosphor bronze) and 6074/2 (Duralumin).

Like the alloy No. 2339C just discussed, the material represented by 3542 is used very successfully for electric resistance heaters, and is essentially an alloy of 80% nickel with 20% chromium, the small amount of manganese (1·41%) being added as in 2339C to assist hot working. The further increase in nickel content to the exclusion of iron as compared with 2339C has, as might be expected, still further improved the ductility in liquid hydrogen to 34·5%.

Monel metal, which is an alloy of 70% of nickel with 30% of copper, shows similar characteristics, although the improvement in ductility is comparatively small. The elongation of 38·5% in liquid hydrogen is slightly greater than for the other materials tested in this research except copper, which showed greater elongation. It is, however, only 2·5% in excess of its normal ductility of 36%. Copper, therefore, although having similar characteristics to nickel as regards improved ductility at low temperatures, would seem to have a somewhat unfavourable influence on this latter metal when alloyed with it.

In phosphor bronze, specimen 6073A, the additions of tin 10·0%, and zinc 1·61%, to copper have had a distinctly unfavourable influence on the latter metal, causing it to deteriorate appreciably, instead of improving, at low temperature.

Duralumin, specimen 6074/2, retains its ductility of 18% almost unimpaired even in liquid hydrogen, a fact which is specially reassuring in view of the use of this alloy in aircraft.

Reduction of Area at Fracture.—In the earlier research at liquid air temperature it was noted that in those metals and alloys whose ductility, as measured by their percentage elongation, was either increased or practically unaltered in liquid air, the reduction in area was lower. The present results have been examined in the same respect.

In six of these eight materials tested—namely, 5277, 2339C, 3542, nickel, copper, and Monel metal—exposure to the temperature of liquid hydrogen has caused a definite increase in their percentage elongation. The ferrous alloy No. 3731 has, however, remained practically unaltered, and the percentage elongation of Duralumin is only slightly reduced. For each of these six materials there is a very definite fall in the reduction of area. Thus for these materials the fact observed at liquid air temperature is confirmed at this lower temperature of liquid hydrogen.

The two materials, No. 3450 and phosphor bronze, show, however, the reverse effect, namely, an increase in their reduction of area figure, although their percentage elongation is reduced by about one-third in liquid hydrogen.

Effects on Tenacity.—While, in accordance with observations at liquid air and other sub-normal temperatures, the general effect is seen to be an increase in tenacity at the temperature of liquid hydrogen, there are important changes. The number of exceptions—that is, materials whose tenacity is actually diminished or shows no increase—is quite considerable, amounting to seven out of 44. In liquid air, although there were some such cases, they were very few, only five out of 129 tests, these, too, comprising a much greater range of materials.

Out of 29 ferrous materials which have been tested both in liquid air and liquid hydrogen, the ratio of increase in tenacity is actually less at the lower temperature of liquid hydrogen in 13 materials, and practically the same in 10 others. Only in the remaining six is the ratio increased.

It would appear, therefore, that, in general, the effect of low temperature in increasing the tenacity of iron and ferrous alloys, also other metals, has reached a limit between the temperatures of liquid air and liquid hydrogen.

At first sight the reason for this might appear to be the brittleness caused by these low temperatures, and intensified at the lower temperature of liquid hydrogen as compared with that of liquid air. It is well known that in the testing of brittle materials premature fracture is liable to occur before their true tenacity can be displayed, notwithstanding the greatest care. In both the liquid air and liquid hydrogen researches the materials which showed a reduction in tenacity had all very small elongations, and one or two also had this even at ordinary temperature. On the other hand, in four materials (Nos. 1240/1, 1291I, 1379B, and 1166A/4) out of six, where the tenacity has, on the contrary, continued to increase progressively between $-182°$ and $-252 \cdot 8°$, the ductility at the lower of these temperatures is also less than 1%. One of the specimens 1166A/4, in fact, shows the greatest relative increase in tenacity in the present series, from 21·4 tons per square inch to 69·2 tons; that is, more than trebled.

Although, therefore, increasing brittleness, no doubt, has an important effect in tending to prevent any further increase in tenacity after the temperature of liquid air is reached, this is not an entirely satisfactory explanation, which remains to be sought.

Owing to this failure of liquid hydrogen temperature to further increase in general the tenacity, especially high tenacity figures are not a feature of the results. Only one, namely, 146·4 tons per square inch for 3671 steel (0·35% C, 0·18% Si, 0·56% Mn, 0·71% Cr, 3·34% Ni), is, in fact, worthy of special mention, as approaching the high figure of 157·2 tons per square inch recorded for the steel " K " (0·41% C, 0·13% Si, 0·96% Mn, 19·91% Ni), in the Report of the Alloys Research Committee (*loc. cit.*), in a test in liquid air.

Effects on Hardness.—In only one specimen, namely 1449A with 31·4% nickel associated with 0·70% carbon, is the hardness appreciably and permanently increased, and this result was to be anticipated in view of the knowledge that this steel is already capable of being transformed in liquid air, and other low temperatures much higher than that of liquid hydrogen. Thus, among the materials tested there is no new and surprising discovery of critical points at temperatures below that of liquid air. Except for the one material mentioned, therefore, it would appear that the extraordinary effects of liquid hydrogen on the mechanical properties of each of the materials are still of the same kind as those caused by liquid air; that is—and it is important to recognize this—the effects are purely temporary, lasting only while the material is subjected to the low temperature, and are not due to any recrystallization or radical change in the metallurgical constituents.

Effects on Microstructure.—Consistently with the indications of the hardness tests, the three materials, namely, Swedish Charcoal Iron, 1010 (1·27% C; 12·69% Mn) and 1414B (1·18% C; 6·05% Mn; 24·3% Ni) out of the four selected for micro-examination, and which showed no change in their hardness after immersion, were unaffected in their microstructure. The photomicrographs obtained from Swedish charcoal iron and 1010 are shown in figs. 4 and 5, Plates 6 and 7.

The photomicrographs, fig. 6 (*a*) and (*b*), Plate 7, of the remaining specimen 1449A (31·4% Ni), on the other hand, had shown a complete change of structure from austenitic to martensitic as the result of immersion in liquid hydrogen, readily explaining the change in hardness from 162 to 317.

Before immersion, in its austenitic condition, the material etches very slowly, and it is with difficulty that the grain boundaries are developed. Pitting takes place at the carbide particles. After immersion, in the martensitic condition, the specimen etches very readily and without pitting.

It should be clearly understood that etching at the temperature of liquid hydrogen is impracticable, so that the structures shown are those which exist after warming up again.

Tensile Properties in relation to Composition.

Group I:—Irons.

In a brief survey of the materials as regards the special characteristics exhibited in the different classes the metal iron takes first place. A progressively increasing tenacity of iron with lowering temperature had been previously demonstrated, although at − 182° C. it had become devoid of measurable ductility. With further reduction in temperature to $-252 \cdot 8°$ the tenacity shows no further increase, and a figure of 52 tons per square inch appears to be about the limit attainable by iron. In this respect, however, as we have seen, it is rather favourably exceptional, most of the materials tested showing an actual falling off in tenacity in this range of temperature.

Group II :—

Class 1*a*. *Alloys of iron and carbon—low Manganese.* *Class* 1*b*. *Alloys of iron and carbon—higher Manganese.*—In liquid air each of these steels, with the exception of the highest in carbon, namely, 1392H with 0·78% carbon, had retained quite an appreciable ductility, from $7\frac{1}{2}$–17%, and so showed themselves not so liable to become brittle as iron itself. 1166A/4 steel with the smallest additions of carbon and manganese (C 0·14%, Mn 0·07%) increased in tenacity from 30 to 61 tons, a quite high ratio (2·65) exceeding that for iron (2·26), while with a medium carbon content of 0·37% in 1397A steel the ratio, 1·94, is still moderately high. For still higher carbon contents, 0·78% in 1392H, the increase in tenacity is comparatively small (ratio only 1·3 to 1·4). It would thus appear that carbon to the amount of about 0·1 to 0·3% has a distinctly beneficial influence both in preventing iron from becoming quite brittle in liquid air and in increasing its effect on the tenacity, but the effect falls off with a higher carbon content.

This conclusion is now borne out and amplified by the results obtained at the still lower temperature of liquid hydrogen. While these low carbon steels have, under the influence of the severe conditions in liquid hydrogen, been unable to retain any further modicum of their ductility, their favourable behaviour is maintained to the extent that they continue to increase in tenacity with this further lowering of the temperature. The already specially high ratio of increase, 2·65, of 1166A/4 steel (0·14% C.) in liquid air is, in fact, carried to 3·23, the original tenacity of 21·4 tons per square inch becoming 69·2 tons. Although many other materials in the present research show a larger tenacity, none shows such a large relative increase as compared with ordinary temperature. With the higher carbon content, 0·37% in 1397A, the same kind of behaviour is exhibited in lesser degree, the carbon percentage being apparently rather too high for the best results.

Even an addition of 1·04% manganese in steel No. 4147/104 (C 0·24%), Group II, Class 1*b*, although harmful, does not appear to remove these characteristics entirely. In this specimen the ratio of increase in tenacity is only moderate, 1·69, but it still retains the characteristic of iron in not suffering any further reduction between liquid air and liquid hydrogen and, as mentioned earlier, retains some ductility in liquid air.

Class 3. *Iron and Aluminium.*—The introduction of aluminium, 0·85% in steel No. 1162D, has hardly affected the special properties mentioned of the low carbon steel.

Class 4. *Iron and Tungsten.*—In steel No. 1294I, Class 4, $7\frac{1}{2}$% tungsten has been added to 0·38% carbon steel. Here again, although the initial tenacity of the steel is considerably increased by the addition, the characteristics of the plain 0·37% carbon steel, 1397A, are retained in all respects.

Class 6. *Iron and Copper*.—The representative of this class, namely, 1263C containing an addition of 2·87% of copper, may be compared with 4147/104, which it was pointed out had some of the merits of low carbon steel, although its tenacity was not increased to the same degree by the low temperatures of liquid air and liquid hydrogen. The addition of copper has very definitely increased this effect on the tenacity, *i.e.*, the tenacity is further reduced, but to the detriment of the ductility at low temperatures above that of liquid hydrogen. In the absence of the apparently—in this connection—harmful influence of the manganese content, it seems quite likely that the copper itself might have as equally an innocuous effect on the special characteristics of low carbon steel as a small percentage of aluminium.

Class 7. *Iron and Nickel*.—The characteristics of the nickel steels have already been discussed to some extent.

With a high percentage of nickel and comparatively low carbon content, specimens 1287L, 3450, and 5277, the ratio of increase in tenacity in liquid hydrogen is only moderate, but here we have to deal with a rather different type of steel from the lesser alloyed steels hitherto considered. These are of the austenitic type with a face-centred cubic atomic structure, while the lower-alloyed steels are ferritic or body-centred. An only moderate tenacity ratio of from 1·42 to 1·78 in liquid hydrogen is characteristic of all except one, No. 3754, of the austenitic ferrous alloys in the present research, and of the metals copper and nickel, which have the same form of atomic structure.

The hardness of 1449A (31·4 nickel) at ordinary temperature has increased from 162 to 317. The large increase in its tenacity at the temperature of liquid hydrogen from 43 to 118 tons per square inch, a ratio of 2·76, was to be expected from the fact that it is permanently transformed, owing to its higher carbon and manganese contents, although be it noted that the increase is no greater than at liquid air temperature.

Class 8*a*. *Iron and Manganese with low Carbon*.—With 15·27% manganese in steel No. 1379D/2, the effect of low temperature in increasing the tenacity is still further reduced, but the rather low ratio of increase is, as in No. 4147/104, 1·04% Mn, maintained the same, at about 1·2, in liquid hydrogen and in liquid air. Also, although its ductility at ordinary temperature was only 5%, it still retained $2\frac{1}{2}$% in liquid air. The effect of manganese cannot, therefore, be regarded as completely unfavourable.

Class 8*b*. *Iron and Manganese with higher Carbon*.—In the presence of a higher carbon content, as shown by steel No. 1010, the behaviour of iron-manganese alloys seems little different, except that at liquid air temperature the loss of ductility is much greater. The small increase in tenacity obtained with a low carbon content is further reduced and, in fact, wiped out, immersion either in liquid air or liquid hydrogen causing very little increase or decrease in tenacity, the ratio of unity for this specimen thus being again preserved with little loss in passing from liquid air to liquid hydrogen.

This specimen, 1010, represents the well-known manganese steel discovered by one of the authors, and the striking change in this extraordinarily tough material when immersed in liquid air, to one almost devoid of ductility, was commented upon at the time of the previous research. This change is all the more mysterious because all other austenitic non-magnetic steels so far tested have, when given their appropriate previous treatment by quenching from a high temperature, retained an excellent ductility of 25% or more in liquid air. The steels of this character when tested in liquid hydrogen have all retained a ductility of 8·5% or more. Such little ductility as manganese steel preserved in liquid air is, on the other hand, completely lost in liquid hydrogen. The individual behaviour of the other austenitic steels will be dealt with later.

Group III :—

Class 1. *Iron, Nickel, and Copper.*—Steel No. 1252B, the representative of this class, with 5·81% Ni and 2·87% Cu has in its normal state only moderate toughness. Its ductility is completely destroyed even in liquid air, and in liquid hydrogen its tenacity actually falls away, by about one-third, from 83 tons per square inch to 56 tons. This is possibly an example where inherent lack of ductility, accentuated by the very low temperature, prevents the true tenacity of the steel being displayed.

Class 2. *Iron, Nickel, and Chromium.*—As with the plain nickel steels, this class includes two types, of low and high alloy content respectively. 1286A with 0·64% chromium and 2·67% nickel, closely resembles in its behaviour in all respects the plain nickel steels of low percentage and similarly annealed, as exemplified by steel 1287D already discussed. The small addition of chromium has apparently little effect in this connection.

The results obtained from the remainder of the steels in this group have already been discussed.

Class 3. *Iron, Nickel, and Silicon.*—It is apparent that the addition of 2% of silicon completely upsets the excellent features of the low-percentage nickel steels, specimen 1103A being devoid of ductility even in liquid air, and further showing only a comparatively small increase in tenacity in liquid air, and even less in liquid hydrogen.

Class 4. *Iron, Nickel, and Manganese.*—The ratio of increase in tenacity shows a slight and progressive increase from 1·48 to 1·63, with increase in nickel content from 14·55% (1109D) to 24·3% (1414B). With a tenacity of 81·0 tons per square inch and a ductility of 25%, this latter alloy, 1414B, with the highest nickel content in this class, although falling short of the properties shown by alloys such as 3754 (18% Cr, 8% Ni) and 5277 (57·5% Ni), can be considered as behaving excellently in liquid hydrogen.

The tests made on 1414A steel (6·05% Mn, 17·91% Ni) after treatment by a slow cooling from 800° C. like the majority of the steels, demonstrates very clearly the inferiority in properties obtained both at ordinary and at low temperatures, as compared with those resulting from the water-quenching treatment appropriate to the austenitic class of steels to which it belongs. A similar result was obtained with alloy No. 1424B in Group IV, Class 2.

Class 7. *Iron, Manganese, and Silicon.*—The alloy tested in this class behaves in much the same way as 1252B steel (iron, nickel, copper). This steel is, in fact, the most adversely affected by liquid hydrogen of any tested in the research.

Class 8. *Iron, Manganese, and Copper.*—The feature of the behaviour in liquid air of steel No. 1240/1 containing 2·01% manganese and 1·45% copper, was the maintenance of its full normal ductility of 17%. Its tenacity was increased in the fairly normal ratio of 60%.

In liquid hydrogen a consistently favourable behaviour is seen, since this steel is among the few whose tenacity progressively increases in passing from liquid air to liquid hydrogen temperature.

As has been seen (specimen 4147/104), such a result is not obtained with the plain low-percentage manganese steels of similar carbon content, and the improvement must therefore be attributed to the addition of copper.

Class 9. *Iron, Chromium, and Aluminium.* *Class* 10. *Iron, Chromium, and Silicon.* *Class* 11. *Iron, Chromium, and Copper.*—All show the same general characteristics whether as regards their behaviour in liquid air or in liquid hydrogen. In each class the test in liquid hydrogen shows a falling off in tenacity, while that in liquid air had shown a small increase.

The carbon content in these three steels is comparatively high, and the properties at liquid hydrogen temperature fall off in order of increasing carbon content from 0·46 to 0·85%. In these circumstances it is not possible to be definite as regards the individual influence of the separate elements. Seeing that the results are inferior in each steel to those obtainable from plain carbon steels of similar percentage, it seems probable that chromium has an adverse influence. The effect of the separate additions of aluminium, silicon, and copper may be relatively small and masked by the influence of the varying carbon content.

Class 12. *Iron, Chromium, and Tungsten.*—With steel No. 1189B having an addition of 1·99% tungsten and 0·66% chromium to 0·26% carbon steel, some ductility is retained in liquid air and the tenacity is raised by a moderate amount (63%). In liquid hydrogen the tenacity falls off. Since in specimen 1294I the much larger amount of tungsten, 7·47%, did not appear to have any serious influence on the low-temperature properties of comparatively low carbon steel, it may be inferred that the deterioration in the present instance is caused by the presence of the small amount of chromium.

Group IV. Iron, alloyed with Three Main Elements :—

Class 1. *Iron, Cobalt, Manganese, and Silicon.*—In specimen 1209C the actual ratio of increase in tenacity in liquid hydrogen, 1·50, is rather less than in liquid air, 1·68. The good properties of 0·25% carbon steel are therefore distinctly deteriorated by the addition of the small percentages of cobalt, 1·8%, manganese, 1·04%, and silicon, 0·64%, although there is a retention of considerable ductility, 12%, in liquid air.

In 4147/104 steel it was seen that 1·04% manganese added by itself had just these effects, but to a lesser extent. There is therefore some slight indication that in the specimen 1209C the further addition of the small amounts of cobalt and silicon have been deleterious to a small extent.

Class 2. *Iron, Nickel, Manganese, and Copper.*—The addition of copper in alloy 1424B appears to have improved the properties of the plain nickel-manganese steel 1109D (Class 4, Group II), as although the tenacity figures are practically identical, the ductility both in liquid air and in liquid hydrogen is distinctly better. In this respect 2·25% of copper has had almost the same result as an increase of 3·36% in the nickel content, from 14·55 to 17·91% (compare steel 1414A). It is interesting to find that under such circumstances copper added to iron can play the same role as nickel.

Class 3. *Iron, Chromium, Manganese, and Silicon.*—This steel, 608, may be dismissed very briefly as one of those which, with 601 and 1252 in previous classes, probably owe their loss of tenacity in liquid hydrogen, and only comparatively slight increase in liquid air, to their inherent lack of ductility, intensified by these low temperatures, preventing them from showing their true tenacity.

Class 5. *Iron, Manganese, Chromium, and Nickel.*—This alloy, No. 2339C, has previously been discussed.

Group IVB. Iron alloyed with Four Main Elements :—

Class 1. *Iron, Chromium, Nickel, Silicon, and Tungsten.*—3731 steel may be said to show the low-temperature properties to be anticipated from a plain austenitic and non-transformable nickel steel of similar nickel content, 27·3%, but to a somewhat enhanced degree. 3450 steel, in fact, with the advantage of rather higher nickel, 35·80%, suffers a reduction in ductility, while that of 3731 steel is unchanged. The additional elements, chromium, 14·60%, tungsten, 3·5%, and silicon, 1·62%, collectively have therefore effected an improvement.

Group V. Non-Ferrous Metals and Alloys :—

The behaviour of the metals in this group as regards their ductility, has already been discussed individually, and little more remains to be said, but they may be summed up as follows :—

Nickel. An only moderate increase in tenacity, 37%, in liquid hydrogen, but this may be due to the rather high initial hardness of the particular specimen tested. Unlike that of iron and most ferrous alloys, the ductility of nickel is increased progressively with reduction in temperature, and at liquid hydrogen temperature it is about double. As has been seen, it is able to confer this characteristic on its alloys with iron, chromium, and copper more or less in proportion to the amounts added.

In copper this characteristic is found to about the same degree. The ductility in liquid hydrogen reaches the extraordinary figure of 60%, far exceeding that of any other material tested in the present research. The superiority of this figure over that of nickel may, however, be due to the specimen of copper having been in a soft and ductile condition prior to immersion. Had the nickel specimen been similarly softened it seems likely that its ductility might have reached approximately the same figure.

Copper, however, does not confer its properties on its alloys with iron in the same way as does nickel, but it is well known that, unlike nickel, it does not form solid solutions with iron, being practically insoluble beyond about a 4% addition. Copper can, however, as has been seen, act in partial replacement of nickel in certain ferrous alloys.

Monel metal and the alloy 3542 may be considered together, both consisting of nickel, alloyed in the one material with 30% copper and in the other with 18·9% of chromium. Their properties resemble those of nickel in a modified degree. While the alloy 3542 shows a rather similar increase, 42%, in its tenacity in liquid hydrogen, its ductility is increased to a greater extent than that of Monel metal, the increase in which is, in fact, only very slight; that is, from 36 to 38·5% elongation.

These characteristics operating on the initially high tenacity and ductility of the nickel-chromium alloy 3542, namely, 59·5 tons per square inch with 27·5% elongation, give it really excellent properties in liquid hydrogen; that is, a tenacity of no less than 84·1 tons per square inch with an elongation of 34·5%.

In phosphor bronze, specimen 6073A, the additions of tin and zinc have clearly destroyed the excellent characteristics of copper. Its ductility, instead of markedly increasing in liquid hydrogen, is very much reduced, and the tenacity shows an increase of only 30%.

In duralumin the favourable characteristics of aluminium, as previously demonstrated in liquid air, are very much deteriorated by the addition of 6% of other elements, chiefly copper. It may reasonably be supposed that the ductility of aluminium, like that of copper and nickel, would be further increased in liquid hydrogen. With duralumin it is practically unaffected.

4. Conclusion.

In conclusion, the authors feel that the further experimental information now obtained has shown the desirability of the extension of the previous researches at liquid air temperature (— 182° C. or 91° absolute) to the much more severe conditions existing at the lower temperature of liquid hydrogen (— 252·8° C., or only 20·3° above the absolute zero).

The explanation for these curious and striking effects of low temperatures on metals yet remains to be sought, and comparatively little attention appears to have been given to this subject by physicists. As regards the increase in tenacity which is in general operative, this may, perhaps, be visualized in an empirical way by an increase in the cohesion brought about by the closer approach of the atoms to each other, due to thermal contraction. This, however, is not entirely satisfactory. There are materials where at this very low temperature of liquid hydrogen the tenacity is actually reduced, and this cannot altogether be explained by the extreme brittleness induced by the temperature. On the contrary, the material No. 1166A/4, 0·14° C., which shows the greatest proportionate increase in tenacity in liquid hydrogen, namely, from 21·4 to 69·2 tons per square inch, a ratio of 3·23, is quite devoid of measurable ductility at that temperature. In other materials (*e.g.*, specimen 1414B) the tenacity is not further increased when the temperature is lowered from − 182° to − 252·8°, even though considerable ductility remains.

Whatever influence closer packing of the atoms may have had on the tenacity, it does not seem to assist in explaining, why iron and many of its alloys become quite brittle, nor the actual improvement in the ductility of nickel, copper, and aluminium and many of their alloys. Such explanations as have been afforded to explain the ductility or otherwise of metals and other crystalline substances have rested on the form of the atomic arrangement rather than on the spacing of the atoms or unit dimensions of the lattice.

In this respect there is a distinct difference between iron, which has the body-centred form of cubic structure, and nickel, copper, or aluminium, which have a face-centred cubic form of structure. This fact, however, does not prevent iron having excellent ductility at ordinary temperature. For atomic structure to be at the root of the question, it is necessary, therefore, to suppose that closer approach of the atoms can, on the one hand, in some way destroy ductility, and, on the other, improve it.

The matter is, too, further complicated by the fact that manganese steel, which has the same face-centred cubic structure as all those other metals and alloys which still retain considerable ductility in liquid hydrogen or even improve, is rendered brittle. That the presence of rather a high carbon content, 1·27%, is not in some way interfering, and preventing the face-centred structure from showing its true characteristics is demonstrated by the following tests specially made to determine this point.

The material for the tests was an alloy, 1379H, containing 0·20% carbon, 0·70% silicon, and 38·9% manganese, and chosen from the series of alloys whose properties were recorded in a paper by one of the authors.* This alloy is remarkably tough, and being of the austenitic or face-centred cubic type of structure like manganese steel, but with a low carbon content, it lent itself especially well to an examination of the present question. Frémont shock tests on notched specimens were made on this alloy both at ordinary and at liquid air temperature, the material having previously been heat-treated by heating to 1,000° C. and quenching in water. The results of the tests were as follows :—

Temperature of test.	Frémont shock test.		Brinell hardness at ordinary temperature.
	KgM to fracture.	Angle of bend.	
15° C.	35·6	157° unbroken	159
− 182° C.	3·2	8°	164
			165 on return to normal.

* Hadfield, 'J. Iron and Steel Inst.,' vol. 115, p. 297 (1927).

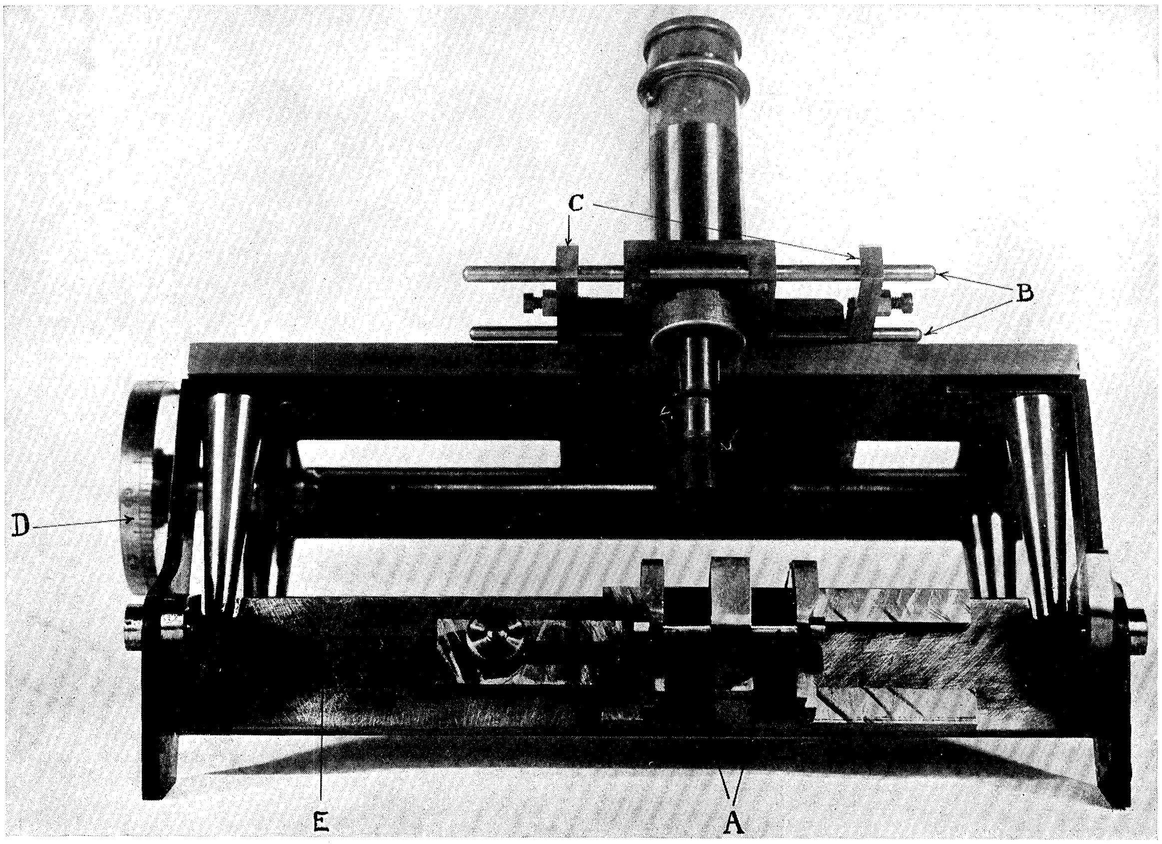

FIG. 3.—Apparatus for measuring elongation and reduction of area of the tensile testpieces.

(*a*) (*b*)

FIG. 4.—Specimen 1010. Manganese steel quenched from 1,000° in water; the structure shows twinning and consists of austenitic grains. (*a*) Before immersion in liquid hydrogen; (*b*) after immersion.

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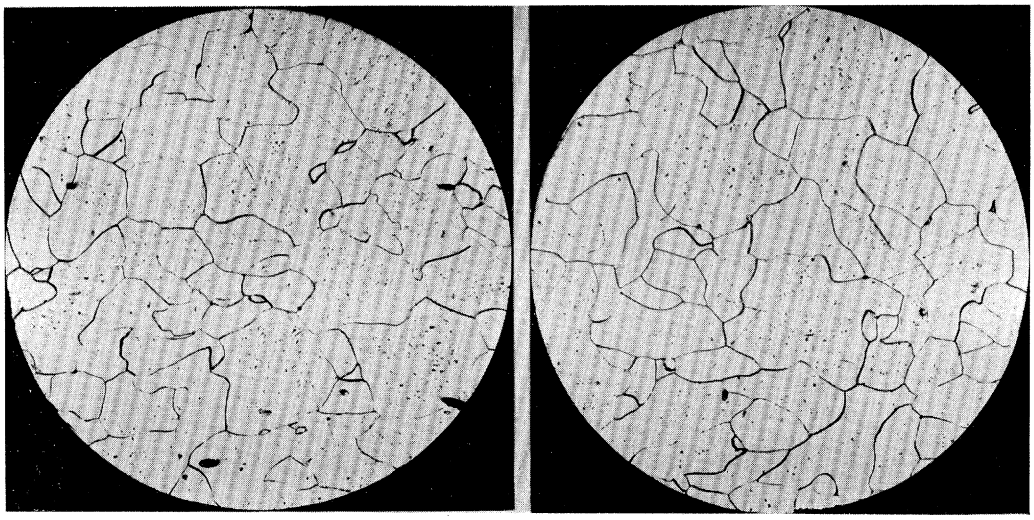
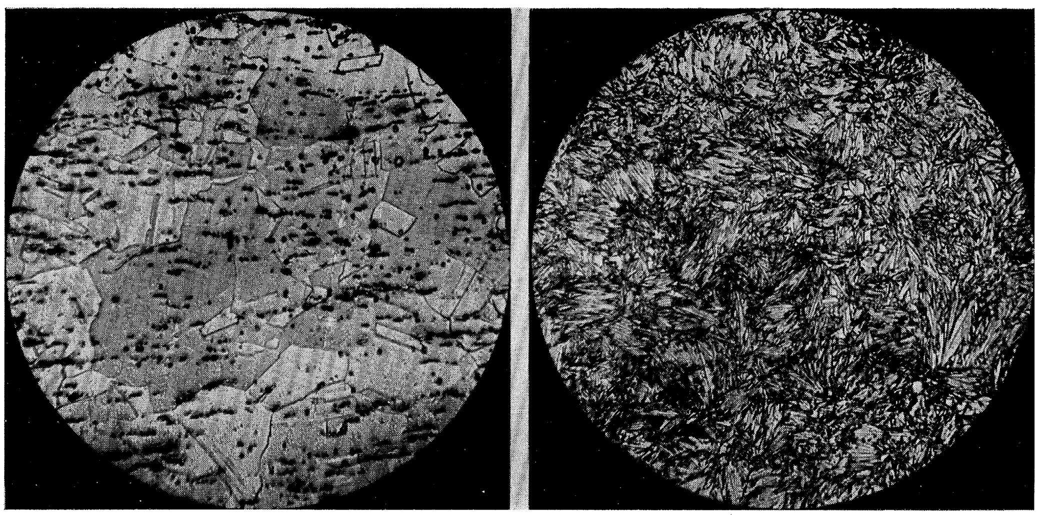


(*a*) (*b*)

FIG. 5.—Specimen 2576. Swedish charcoal iron; the structure consists of ferrite grains. (*a*) Before immersion in liquid hydrogen; (*b*) after immersion. × 200.



(*a*) (*b*)

FIG. 6.—Specimen 1449A (31·4% Ni). (*a*) Before immersion in liquid hydrogen. Ground mass of austenitic grains with globules of free carbide (dark particles). (*b*) After immersion, an acicular martensitic structure. × 200.

(*a*) Brinell hardness 162″, specific magnetism 20%.
(*b*) ,, ,, 317″, ,, ,, 90%.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Thus the excellent toughness and ductility of this iron-manganese alloy low in carbon is practically destroyed in the same way as with manganese steel, and the anomaly remains that a face-centred cubic structure does not necessarily ensure ductility at low temperature.

A further possibility is that the structure undergoes some radical change at low temperature with iron and those alloys which become brittle, and not with nickel and the other metals and alloys, or *vice versa*. The progressive increase in brittleness or improvement in ductility with reduction in temperature, in those cases which have been sufficiently explored, rather seems to disprove this.

To investigate the point one of the authors proposes, with the kind permission of Professor Sir WILLIAM BRAGG at the Royal Institution, to have examined there the actual structures of certain crucial specimens in this region of specially low temperature. In this direction the microscope does not appear to help, since as stated above methods for the examination of structures at low temperatures are not available.

The interesting behaviour of nickel, copper, and aluminium make the prospect of tests on these metals at still lower temperatures very attractive; that is, when present difficulties of doing so can be overcome. One may reasonably ask, certainly for copper, whether it is tending towards a condition, at or near the absolute zero, of perfect ductility.

Finally, there is the interesting fact that carbon, when added to iron in a sufficiently small amount, namely, about 0·1 to 0·3%, actually helps to prevent it becoming brittle. Although it is not effective in this way in liquid hydrogen, *i.e.*, iron is made brittle at this temperature even with this addition of carbon, it, nevertheless, improves the ratio by which the tenacity is increased. With a higher carbon addition the low-temperature properties of the pure iron are deteriorated.

This peculiar effect of carbon is certainly most puzzling, and until a more intimate knowledge of the changes brought about in the internal structure of metals by low temperatures is acquired, a complete explanation of this and the other features previously mentioned can hardly be expected.

A bibliography dealing with this work has been deposited in the library of the Royal Society by one of us (R.H.).

Summary.

This paper deals with the effect of low temperatures on the mechanical and physical properties of various metals and alloys. It extends the previous work of one of the authors (HADFIELD) from the temperature of liquid air, — 182° C., to that of liquid hydrogen, — 252·8° C.

Iron, ordinary steels, and most of the alloys of iron which at — 182° C. retained a slight degree of toughness, are devoid of ductility at — 252·8° C., though those containing a comparatively high percentage of nickel still retain remarkable ductility.

Thus alloy No. 5277, Table 2, with 57·50% of nickel possesses at — 252·8 an elongation of no less than 35·5% with a tenacity of 73·3 tons per square inch.

The metal nickel is found to be really stronger and tougher at — 252·8° than it is at ordinary (say, room) temperature. At the latter temperature the yield point is 40·70 tons, the tenacity 46·90 tons per square inch, the elongation 11·50%, and the reduction of area 71·00%; at — 252·8° C. the figures are increased to 52·40 tons yield point, 64·40 tons tenacity, 21·50% elongation, and 64·00% reduction of area; the ball hardness being at normal temperature 127, at — 182° C. 200, and at — 252·8° C. (deduced from the tensile test) 302, returning to 218 at normal temperature.

The mechanical properties of nickel, copper, and aluminium improve with the lowering of temperature down to — 252·8° C. At this temperature copper possesses a tenacity of 29·70 tons per square inch, with an elongation of no less than 60%.

The general effect of low temperatures in increasing the tenacity of iron and ferrous alloys, and also of other metals, appears to have reached a limit between the temperatures of — 182° C. and —252·8° C. At the latter temperature iron maintains its tenacity of 52 tons per square inch, the same figure as that obtained at — 182° C.

Carbon in very small amount, 0·1 to 0·3%, added to iron appears to minimize its becoming brittle, and, further, causes its tenacity to undergo a continued increase below — 182° C. At — 252·8° C. the tenacity of specimen No. 1166 A4, 0·14% C; 0·08% Si; and 0·07% Mn, is more than trebled, reaching 69·20 tons per square inch.

The effects of a temperature of —252·8° C. on the mechanical properties are in general only temporary, the various materials entirely recovering their normal condition at ordinary temperatures. The alloy No. 1449A, Table 2, with 0·70% C, 0·82% Mn, 31·40% Ni is an exception, this being a representative of those alloys containing a comparatively high percentage of nickel. These special alloys, with a sufficient content of carbon, manganese, or other element, have long been known to be of an irreversible character. Photographs of the structures before and after exposure to —252·8° C. are shown.

The rendering brittle at — 252·8° C. of properly toughened—that is, water quenched—manganese steel appears to be entirely unaccompanied by changes in its metallographic or non-magnetic character. Its behaviour is in marked contrast with that of other austenitic ferrous alloys containing nickel. Of this latter type the representative materials tested either do not suffer any loss in ductility, or if they do are not rendered so brittle as manganese steel. Further, some of them undergo a transformation of structure from austenitic to martensitic, *e.g.*, specimen No. 1449A (0·70% C and 31·40% Ni).

We gladly express thanks to our assistants, Mr. G. J. FLIM, Mr. C. COPPVOLSE, and Mr. J. W. BLOM at Leiden, and to Mr. S. A. MAIN and Mr. T. G. ELLIOT at Sheffield, for the valuable help they have rendered during these experiments and the preparation of this paper.

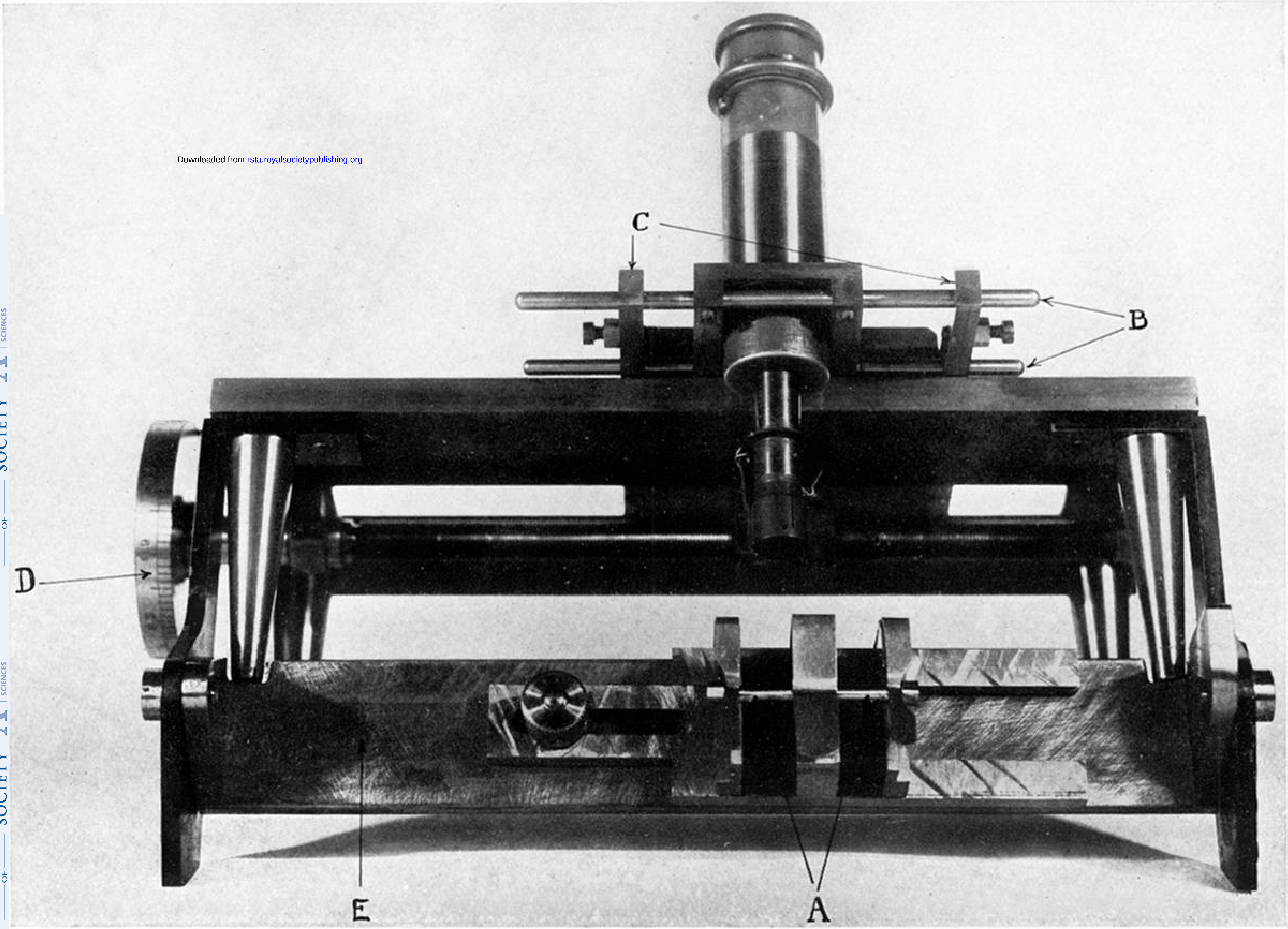


FIG. 3.—Apparatus for measuring elongation and reduction of area of the tensile testpieces.

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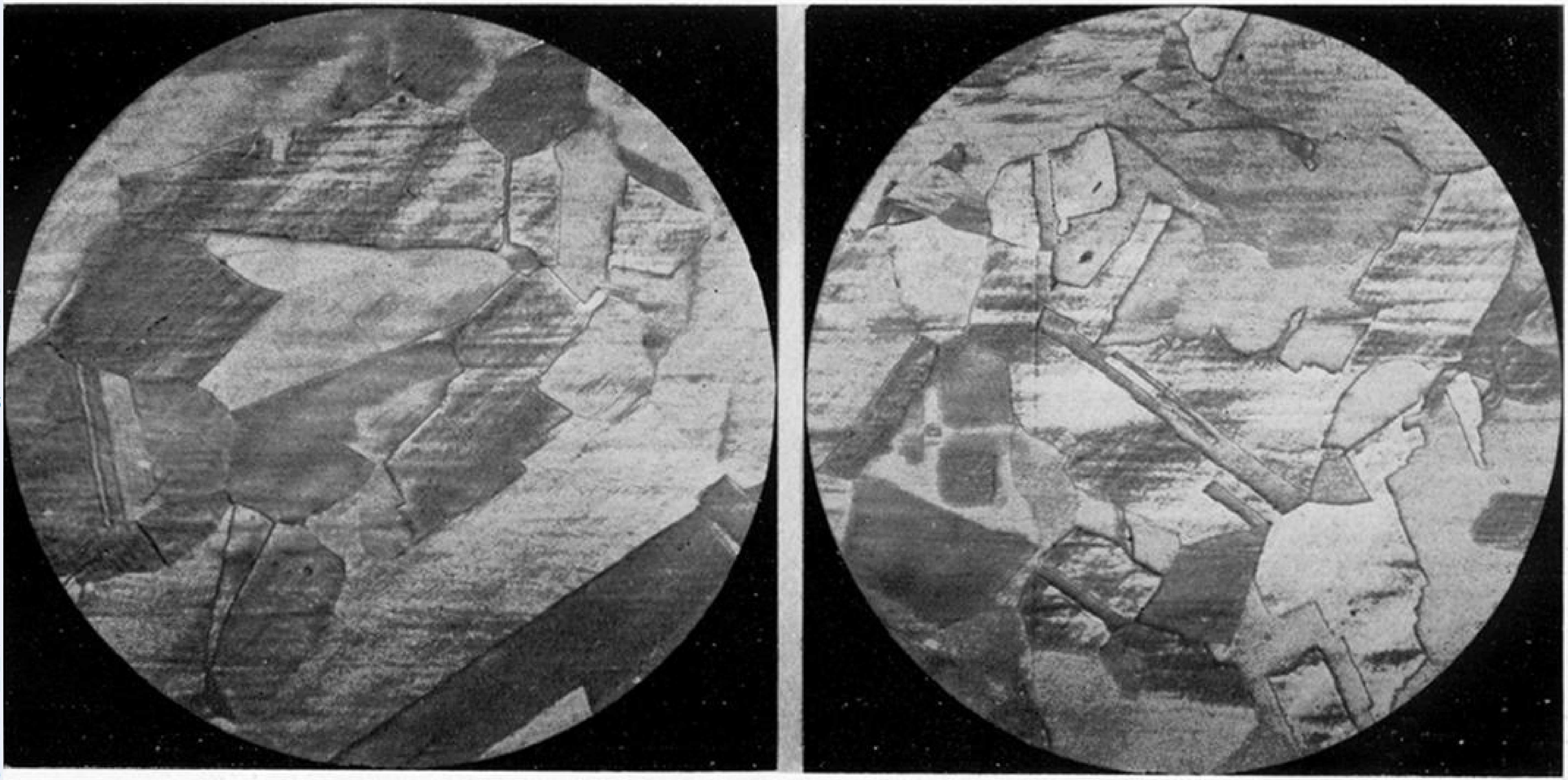

(*a*) (*b*)

Fig. 4.—Specimen 1010. Manganese steel quenched from 1,000° in water; the structure shows twinning and consists of austenitic grains. (*a*) Before immersion in liquid hydrogen; (*b*) after immersion.

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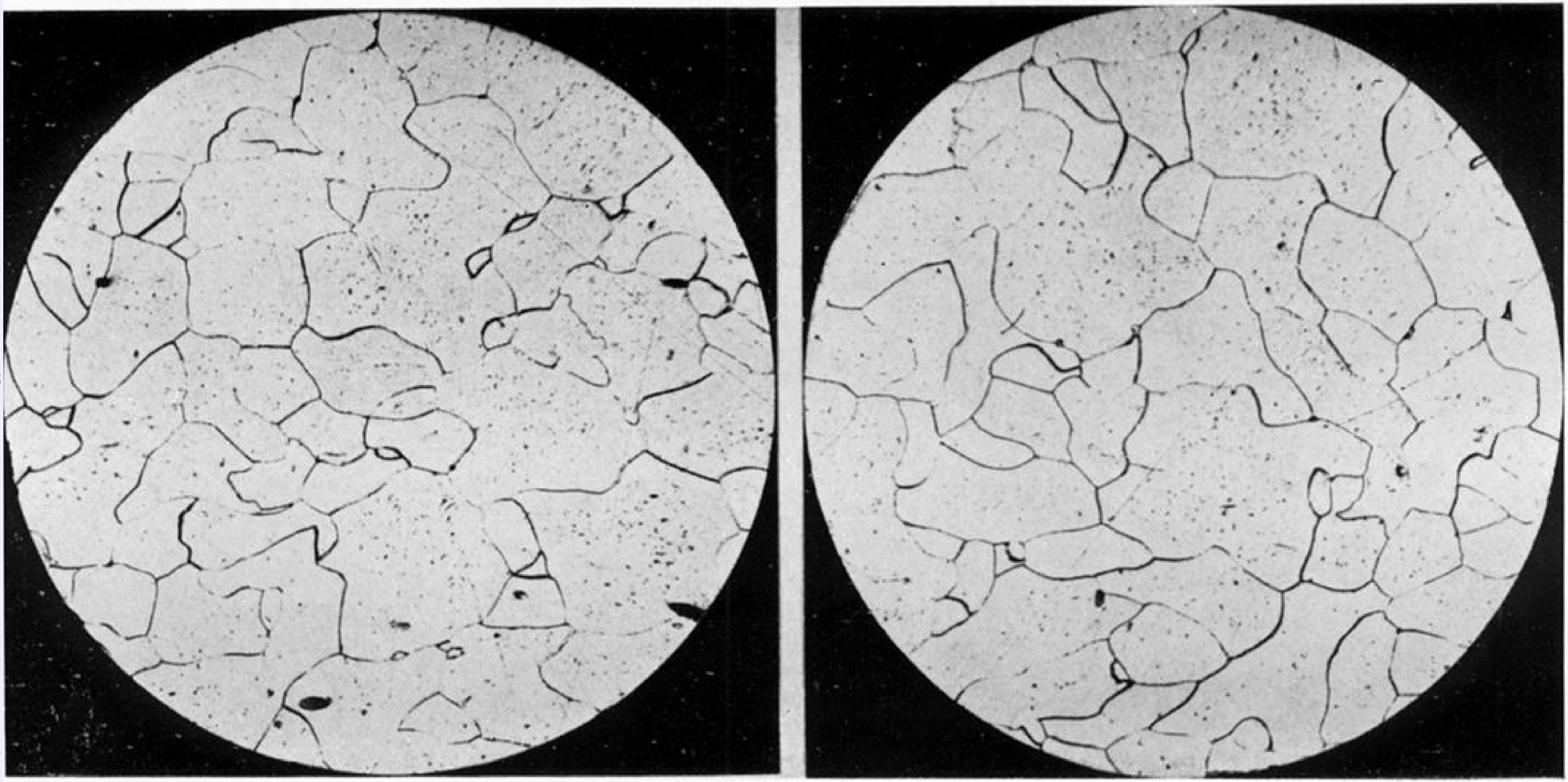
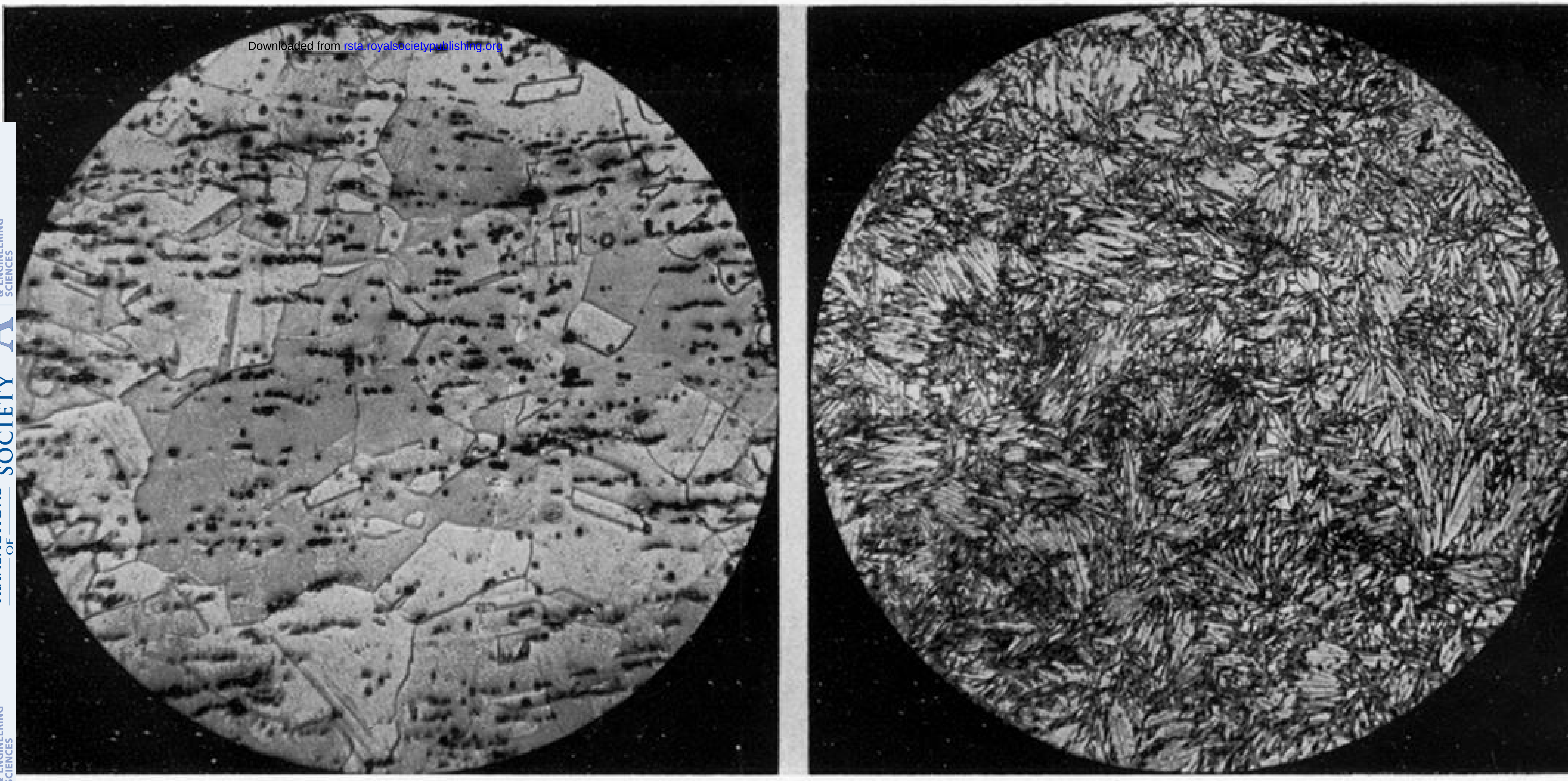


(*a*) (*b*)

FIG. 5.—Specimen 2576. Swedish charcoal iron; the structure consists of ferrite grains. (*a*) Before immersion in liquid hydrogen; (*b*) after immersion. $\times$ 200.



(a) (b)

Fig. 6.—Specimen 1449A (31·4% Ni). (a) Before immersion in liquid hydrogen. Ground mass of austenitic grains with globules of free carbide (dark particles). (b) After immersion, an acicular martensitic structure. × 200.

(a) Brinell hardness 162″, specific magnetism 20%.
(b) ,, ,, 317″, ,, ,, 90%.

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