

“Ghost Lines”*

Phenomena Observed in Large Steel Castings

By J. O. Arnold, D.Met. F.R.S. Professor of Metallurgy in the University of Sheffield

DURING the past twenty years the author has occasionally been requested to investigate the phenomena of “ghosts” in forgings from large steel ingots, ranging in weight from about 40 to 80 tons. An exact knowledge of the method of formation and the nature of “ghost lines” is a matter of great importance both to steel metallurgists and to naval engineers.

In 1894 the author and Mr. Rudolf Leffler, Associate in Metallurgy of the University of Sheffield, made a pioneer investigation of the nature of the “ghost lines” in a large steel forging made from a 40-ton ingot, from the upper portion of which about 30 per cent had been cut away to scrap. During turning operations, the “ghost lines” in this forging, which were of a very decisive character, showed up white and in slight relief against the steel-gray color of the mass of the turned forging. When exposed to the sulphurous atmosphere of Sheffield over the week-end, the white “ghost lines” turned light brown, owing to oxidation. By means of a fine and sharp engraver’s tool a number of the “ghost lines” were dug out, and similar minute excavations were made on parallel lines on portions of the forging free from “ghosts.” Of course, the shavings taken along the “ghost lines” were, to use an Irishism, contaminated with some steel free from “ghosts.” The two sets of shavings, on analysis, registered the following figures:

ANALYSIS OF “GHOST”—FREE PORTIONS OF THE FORGING.

	Per Cent.
Carbon.....	0.320
Silicon.....	0.080
Manganese.....	0.680
Sulphur.....	0.020
Phosphorus.....	0.035

ANALYSIS OF SHAVINGS FROM PORTIONS OF FORGING SHOWING “GHOSTS.”

	Per Cent.
Carbon.....	0.380
Silicon.....	0.310
Manganese.....	0.920
Sulphur.....	0.045
Phosphorus.....	0.050

The foregoing figures show that the inclusion in the steel shavings of some “ghost lines” had raised the carbon 19, the silicon 287, the manganese 35, the sulphur 125, and the phosphorus 44 per cent, the “ghost”-free figures being taken as 100 per cent.

Micrographic Examination.—The microstructure of the “ghost lines” showed the presence of excessive streaks of dove-gray sulphide of manganese, and of excessive carbon in the form of troostitic pearlite, and the latter caused the “ghost” to etch dark brown—indeed, almost approaching black. Greenish vitreous streaks of Stead’s silicate of manganese, or, possibly, bisilicate of manganese and aluminium, were also present, causing the notably high silicon and manganese in the steel shavings containing the “ghost.”

It is now obvious that the elements showing true segregation were carbon, sulphur, and phosphorus, while the silicates probably formed while the steel was running down the lander from the furnace, and were incidentally involved in the steel. The author will hereinafter exhibit titanic “ghosts” almost free from silicates. In these circumstances it is most unfortunate that the true migratory elements are usually included in the general and inaccurate term “slag inclusions.” The latter are either accidental or incidental, while sulphide of manganese is an absolutely normal and unavoidable constituent of all steels, excepting high-speed tool steels, in which the sulphur exists in solid solution as non-injurious sulphide of tungsten (WS₂), a fact ascertained in a semi-private, but somewhat extensively circulated, research, the results of which were issued by the author about a year ago under the new copyright regulations. A printed copy of the research was deposited officially by the Registrar in the archives of Sheffield University.

The Genesis of “Ghost Lines.”—On April 10th, 1908, the author, at the request of the late Sir William H. White, read in London, at the meeting of the Institution of Naval Architects, a paper entitled “Factors of Safety in Marine Engineering.” An extract from this, headed “On Ghost Lines,” is produced below, together with

some of the photomicrographs illustrating the paper above referred to.

On “Ghost Lines.”—In a big ingot, irrespective of the liquated and scrapped upper third, in parts of which the phosphorus, for instance, may exceed one per cent, there is always more or less a segregation of the mobile elements, carbon, sulphur, and phosphorus, to a series of centers. Investigations on “The Diffusion of Elements in Iron,” carried out at the Sheffield University College, and published in the *Journal of the Iron and Steel Institute*, No. 1, 1899, indicated the mobility of carbon to be about five times as great as that of sulphur, phosphorus, and nickel. A photomicrograph shows a dark-etching nodular segregation area. This consists of iron containing an undue proportion of (a) an isomorphous mixture of the double carbides of iron and manganese ($x\text{Fe}_3\text{C}$, $y\text{Mn}_3\text{C}$); (b) dissolved phosphide of iron (Fe_3P); (c) small segregated irregular globules of sulphide of manganese (MnS). On forging the ingot the angular or martensitic structure is broken up, while the nodular segregate is drawn out into a dark-etching rod. In such a forging the elongated segregation, which is relatively hard, is in turning operations jumped by the tool, leaving in faint relief a relatively white line; hence, the turner’s somewhat far-fetched name “ghost.” During the prolonged cooling at a low, red heat, the carbonized “ghost” becomes decarburized, the dissolved phosphide of iron seeming to expel the hardenite (transformed pearlite) to the edges of the “ghost line,” the final product being the decarburized “ghost line.” Here the “ghost” has become essentially a broken and irregular cylinder of pearlite, filled with pale-brown etching ferrite, containing emulsified phosphide of iron, through which is scattered short rods of dove-gray sulphide of manganese.

The Mechanical Effect of “Ghosts” on the Engineering Efficiency of Large Marine Propeller Shafts.—The author was requested to decide whether or not the presence of moderately large “ghost lines” in a propeller-shaft, forged from the lower end of an 80-ton ingot, was mechanically dangerous under torsional stresses and strains, and he has been permitted to quote the substance of his report:

Report on “Ghost Lines” in a Large Propeller Shaft.—I examined in the lathe a propeller shaft which I was told was for a cruiser, and had been forged from an ingot weighing about 80 tons. I examined the turned shaft for “ghost lines,” which are always present in large masses of forged steel. They were clearly visible, especially on the coned end. As you had requested me to ascertain the exact influence of these “ghost lines” on the mechanical properties of the steel, it was necessary to cut up the end of this shaft for experimental purposes. The shaft was sampled so as to get sets of test-bars visually containing well-marked “ghost lines,” all such samples being marked “B,” and similar sets exhibiting hardly any “ghost lines,” these latter samples being marked “G.” On this basis two pairs were taken for tension tests, two pairs for torsion tests, and six pairs for alternating-stress tests.

On the Nature of “Ghost Lines.”—The results of recent research in the Metallurgical Department of Sheffield University indicate that “ghosts” are formed in large ingots by segregation in the following manner: Just before the ingot solidifies, a definite alloy of iron with sulphide of manganese freezes out from solution, and segregates to a series of centers. These frozen masses seem to form nuclei, around which gather the migratory elements of steel—namely, carbon, sulphur, phosphorus, and, if present, nickel. Thus is obtained a more or less globular compound segregate, which is somewhat variable in composition, but with an average constitution approximately as follows:

COMPOSITION OF MAIN MASS OF INGOT. COMPOSITION OF “GHOST” GLOBULES.*

	Per Cent.		Per Cent.
Carbon.....	0.30	Carbon.....	0.39
Sulphur.....	0.04	Sulphur.....	0.12
Phosphorus.....	0.06	Phosphorus.....	0.10

On forging, the “ghost globules” relatively high in carbon, sulphur, and phosphorus are drawn out into strings, which, on turning, exhibit themselves as the well-known “ghost lines.” In an annealed shaft, such as that

* A decarburized “white ghost” is relatively soft and is “dragged” by the tool, leaving a faint depression.

* This curious action of dissolved phosphide of iron was first pointed out by Dr. J. E. Stead, F.R.S.

now under consideration, these “ghost lines” are always “white ghosts” when viewed under the microscope. The “ghost line” is, in fact, a streak of iron free from carbon, but containing in solid solution, and hence, invisible, the phosphide of iron, which has expelled the carbon to the edge of the “ghost.” The sulphur is scattered through the iron of the “ghost” in the form of dove-gray streaks of manganese sulphide. I may point out that “ghost lines” can never be eradicated from large masses of forged steel until metallurgical science has entirely eliminated sulphur from steel. This, I fear, will not happen in our time, if ever.

The General Mechanical Influence of “White Ghosts.”—“White ghosts,” as I have already pointed out, are a succession of streaks of carbonless iron containing about 0.10 per cent of dissolved phosphorus and about the same percentage of sulphur, the latter presented as visible streaks of sulphide of manganese. A rough-and-ready rule to convert the percentage of sulphur by weight into percentage of sulphide of manganese by volume is to multiply by 5; hence the volume percentage of manganese sulphide in “ghosts” generally is about 0.5 to 0.6 per cent. It should, however, be remembered that the volume of the alloy of iron and sulphide of the manganese which first froze out would constitute several per cent of the mass of the “ghost.”

So far as my experience goes “ghost lines” are little detrimental to the mechanical properties of structural steel, so long as the plane of stress is at right angles to the direction of the “ghost lines;” in other words, when the material is in tension, torsion, or under alternating stresses.

With a reasonable factor of safety (say $3\frac{1}{2}$ on the elastic limit) I have never heard of a propeller shaft breaking in tension or torsion, but always under alternating stresses, the plane of rupture being at right angles to the “ghost lines” and on the theoretical plane of maximum stress at the outboard end of the liner, say about 1 inch aft of the propeller boss. With such fractures “ghosts” have little or no connection.

INVESTIGATION OF THE MECHANICAL PROPERTIES OF THE SHAFT.

STATIC TENSILE TESTS.—ALL THE TEST-PIECES WERE 2 INCHES PARALLEL, 0.564 INCH DIAMETER, 0.26 INCH SQUARE AREA.

Mark.	Yield-Point.	Maximum Stress.	Elongation.	Reduction of Area.	Fracture.
	tons per sq. in.	tons per sq. in.	per cent on 2 in.	per cent	
4200 F G 4	18.32	30.20	35.5	59.74	Fine gray, granular
4200 F G 5	16.30	30.84	35.5	52.17	“ “
4200 F B 1	15.00	30.20	35.0	60.41	“ “
4200 F B 4	15.40	32.80	37.0	65.14	“ “

The figures in the foregoing table all denote a structural steel of very good quality and of generally even texture. Any slight variations are due to the fact that in annealing such shafts the texture of the pearlite (steel area) always varies a little, some regions being somewhat more laminated, and hence milder, than others. Extensometer tests were taken on each test-bar, and a typical curve was plotted, in which the true elastic limit is indicated at about 14 tons per square inch, and the yield, or breakdown, point, as about 17 tons per square inch.

STATIC TORSION TESTS.—ALL TEST-BARS WERE 6 INCHES PARALLEL, AND 0.8 INCH IN DIAMETER OR 0.5 SQUARE INCH IN AREA.

Mark.	Stress Endured in Pounds.	Angles of Rotation Endured.	Remarks.
		degrees.	
4200 F G 7	7721	1745	Previous to testing, a straight ink line was ruled along each test-bar.
4200 F G 6	7459	1578	The spirals on the fractured bars mark the torsional movement during the test-operations.
3200 F B 5	7647	1909	
4200 F B 7	7425	1631	

Dynamic or Alternating Stress Tests.—The following tests were made on an Arnold stress-strain machine under standard conditions—namely, burnished test-bars 6 inches long by $\frac{1}{2}$ inch diameter; distance from zero of stress to plane of maximum stress, 3 inches; deflection at stress, $\frac{1}{2}$ inch each way; rate of alternation, 650 per

* Paper read before the British Institution of Mechanical Engineers.

minute. The results are embodied in the following table. The grand means of each include twelve tests each.

TABLE OF DYNAMIC STRESS TESTS.

Mark.	First Test.	Second Test.	Mean.	Grand Mean.
G 1	254	258	256	246
G 2	258	230	244	
G 3	250	252	251	
G 1 ₂	264	232	248	
G 2 ₂	25	240	247	
G 3 ₂	230	230	230	278
B 2	282	254	268	
B 3	244	264	254	
B 5	286	280	283	
B 2 ₂	298	290	294	
B 3 ₂	294	282	288	
B 5 ₂	248	274	261	

Curiously enough, the samples selected as having marked "ghost lines" give better results. The tests present nothing remarkable, being such as are generally given by a shaft forged from a large ingot and subsequently moderately annealed. The absence of over-annealing in the sense of too slowly cooling is evidenced by the stress-strain diagram already referred to.

Conclusion.—An examination of the fractures of the whole of the test-pieces—namely, eight in tension, eight in torsion, and forty-eight in alternation—exhibited at the respective points of rupture no signs of cracking or opening due to "ghost lines," or to any other cause. I am therefore of opinion that no risk would be incurred by putting similar shafts into the vessels building.

Examination of the "Ghosts" in a Large Ingot as Cast.—Comparatively recently the author had an opportunity, quite unique in character, of ascertaining the exact nature of unforged "ghosts," some of which were about 5/8 inch in diameter and 9 inches long. The details of the extraordinary circumstances in which these gigantic "ghosts" were obtained, to the number of perhaps fifty, are as follows:

A mild-steel chrome-nickel ingot, weighing (together with its feeding head) about 57 tons, was being cast, and the casting was just completed when a burst-out occurred at the bottom. The time record was as follows: Casting was commenced at 8.57 P. M., steel entered the feeding-head at 9.23 P. M., and the casting was finished at 9.28 P. M. The burst-out occurred five minutes later, at 9.33 P. M., but was stopped at about 9.35 P. M. When cold it was found that the ingot was hollow for 21 inches down, having "bled" about 17 tons of steel. The ingot was 60 inches octagon at the top by 46 inches octagon at the bottom and 156 inches long. On cutting off the hollow portion of the ingot and then cutting this portion longitudinally into four pieces, a most extraordinary discovery was made. In each octagonal angle was found a series of protruding frozen "ghosts." With so much material available, it was easy to make an exhaustive chemical and microscopical examination of these "ghosts," some of which were protruding to an extent of 3/8 inch. The surfaces of the steel free from "ghosts" showed decisive projecting indications of octahedral crystallization. The "ghosts" seemed to have caught on the angle where the body of the ingot turns upward to the feeding head, seeming to have been mechanically trapped on what may be termed a series of metallurgical futtock shrouds.³ A complete set of "ghosts" from one angle was chipped away flush with the main body of the solidified shell of the ingot and was carefully analyzed. Drillings were also taken in a region free from "ghosts." The results are embodied in the following table:

Element.	Disc. Drillings.	"Ghost" Chippings.
	<i>Per Cent.</i>	<i>Per Cent.</i>
Carbon.....	0.19	0.27
Manganese.....	0.53	0.5
Silicon.....	0.168	0.215
Sulphur.....	0.037	0.157, 0.117, 0.075; mean 0.12
Phosphorus.....	0.028	0.084, 0.101, 0.090, 0.054; mean 0.082
Chromium.....	0.75	0.74
Nickel.....	3.74	4.24

From the foregoing table it is obvious that the "ghosts" are compound and variable segregates, marked segregations of carbon, sulphur, phosphorus and nickel having taken place. In the *Journal of the Iron and Steel Institute*, No. 1, 1899, the author and Dr. McWilliam published a paper on "The Diffusion of Elements in Iron." They showed that at about 1000 deg. Cent. the elements of steel divided themselves into two groups—namely, migratory and non-migratory elements. The migratory group included the elements carbon, sulphur, phosphorus and nickel. The above table shows that the conclusions arrived at for a temperature of 1000 deg. Cent. also hold good for 1500 deg. Cent., at which temperature the steel is fluid. The chemical figures are somewhat astounding. It has been a generally accepted canon of metallurgical

faith that "ghosts," being higher in carbon, sulphur and phosphorus than the main mass of the steel, necessarily froze last. The data presented in this research, however, prove conclusively that the "ghosts" freeze first at many degrees above the main-mass freezing-point. Protrusions of frozen "ghosts," some of them 9 inches long, with projections into the fluid mass of 3/8 inch, are facts which cannot be disputed, although opposed to generally accepted theories. The behavior of nickel would seem to be connected with a fact published before the Institution of Mechanical Engineers in March, 1914, by the author and Prof. A. A. Read (*Engineering*, April 3d, 1914), that nickel when present up to, say, 5 per cent does not associate itself with the carbon, but forms a definite alloy with iron corresponding to the formula FeNi, and hence contains 13 per cent. nickel. This nickelide of iron has, as received from the rolls, a yield-point of nearly 60 tons per square inch, a maximum stress of nearly 90 tons per square inch, associated with an elongation on 2 inches of 11 per cent, and a reduction of area of 46 per cent. It is therefore perhaps the most remarkable metallic compound of iron.

The Formation of "Ghosts."—In two papers on "The Forms in which Sulphides may Exist in Steel Ingots," published respectively in the *Journal of the Iron and Steel Institute*, No. 1, 1914 (*Engineering*, May 22d, 1914), and No. 1, 1915, the author and Mr. G. R. Bolsover showed the existence of a definite solution or compound of iron and sulphide of manganese, which appeared to freeze before the main mass of the ingot, and on cooling broke up into a mixture of iron and dots of sulphide of manganese. The composition of this mixture was tentatively suggested as 88 per cent Fe+12 per cent MnS. Such a composition would be obviously of a relatively low specific gravity, and would tend to rise through the still unfrozen main mass of the steel. The author suggests that as this definite substance rises in a thick paste or semi-frozen state, it forms in different parts of the ingot nuclei which gather to themselves the migratory compounds of steel—namely, carbide, phosphide, and, in nickel steels, nickelide of iron. The author also suggests that the extraordinary gigantic "ghosts" present in each octagonal angle of the "bled" ingot described in this paper, were formed in the manner above enunciated.

APPENDIX.

Since formulating the futtock-shroud theory to explain the irregularly drawn-out nature of the "ghosts" in the cast ingot, the author has made a further careful examination of the "ghosts," and has come to the conclusion that the true explanation seems to be that after casting, at a position at the top of each ultimate "ghost line," was a segregate of roughly globular form. Then the rapid downward rush of many tons of molten steel when the break-out took place, acted upon each paste and more or less globular segregate in a manner similar to that of hammering or rolling, and drew them out into the elongated masses found grouped at each octagonal angle. The roughly globular rising masses of segregate all appear to have migrated into the angles, because the steel in those angles was at a higher temperature than the steel on the slightly radial sides of the octagon, the reason of this being that the solidified white-hot steel at the angles was thicker than that on the sides of the octagon, and hence more effectively lagged the fall of temperature at the angles as compared with that taking place through the sides of the relatively cold mold.

How Stone is Sold

OWING to the variety of uses to which stone is put, there is no regular unit of measurement employed by the quarryman, the stone being sold by the cubic yard, cubic foot, ton, cord, perch, rod, square foot, square yard, square, or other unit. Building and monumental stone, especially the dressed product, is usually sold by the cubic foot or the cubic yard, although this unit varies with the class of stone and with the locality. A large quantity of the rough stone is sold by the perch, cord, or ton. Rubble and riprap, including stone for such heavy masonry as breakwater and jetty work, are generally sold by the cord or ton. Fluxing stone and stone for chemical use—as for alkali works, sugar factories, carbonic acid plants, and paper mills—are sold by the long ton. Flagstone and curbstone are sold by the square yard or the square foot, the thickness being variable and dependent on the orders received. Granite paving blocks are sold invariably by the number of blocks, but the blocks are not of uniform size, the value depending on the size and the labor necessary to cut the block into the shape desired. Other paving material is sold by various units, such as the ton or cubic yard. Crushed stone is reported as sold by the cubic yard or ton, the short ton being more generally used.

The perch is legally defined in many older States as 24 1/2 cubic feet; in some States, and even within a single State, it varies from 16 1/2 through 20, 22, 25, to 27 cubic feet, and in others it is defined as equivalent to 2,200, 2,500, 2,700, 2,800, and 3,000 pounds. The cord in some States is measured in feet—for instance, 128 cubic feet

in the quarry or 100 feet in the wall; in others it denotes weight and is variously defined as equivalent to 11,000, 12,000, 12,500, and 13,000 pounds. The weight of a cubic yard of crushed stone varies from 2,300 to 3,000 pounds, the average weight being about 2,500 pounds. In certain localities this crushed stone is sold by the "square" of 100 square feet by 1 foot, or 100 cubic feet. It is also of interest to note the selling of crushed stone by the bushel, 21 1/2 bushels representing a cubic yard of about 2,700 pounds. As most of the crushed-stone producers report the quantity according to some unit, it has been possible to convert the crushed stone into short tons, the unit which represents the larger number of producers and is the most convenient. —*Mineral Resources of the U. S.*, II, 33.

SCIENTIFIC AMERICAN SUPPLEMENT

Founded 1876

NEW YORK, SATURDAY, APRIL 8, 1916.

Published weekly by Munn & Company, Incorporated
Charles Allen Munn, President; Frederick Converse Beach,
Secretary; Orson D. Munn, Treasurer;
all at 233 Broadway, New York

Entered at Post Office of New York, N. Y., as Second Class Matter
Copyright 1916 by Munn & Co., Inc.

The Scientific American Publications

Scientific American Supplement (established 1876) per year \$5.00
Scientific American (established 1845) " " 3.00

The combined subscription rates and rates to foreign countries,
including Canada, will be furnished upon application

Remit by postal or express money order, bank draft or check

Munn & Co., Inc., 233 Broadway, New York

The purpose of the Supplement is to publish the more important announcements of distinguished technologists, to digest significant articles that appear in European publications, and altogether to reflect the most advanced thought in science and industry throughout the world.

Back Numbers of the Scientific American Supplement

SUPPLEMENTS bearing a date earlier than January 2nd, 1915, can be supplied by the H. W. Wilson Company, 39 Mamaroneck Avenue, White Plains, N. Y. Please order such back numbers from the Wilson Company. Supplements for January 2nd, 1915, and subsequent issues can be supplied at 10 cents each by Munn & Co., Inc., 233 Broadway, New York.

We wish to call attention to the fact that we are in a position to render competent services in every branch of patent or trade-mark work. Our staff is composed of mechanical, electrical and chemical experts, thoroughly trained to prepare and prosecute all patent applications, irrespective of the complex nature of the subject matter involved, or of the specialized, technical, or scientific knowledge required therefor.

We also have associates throughout the world, who assist in the prosecution of patent and trade-mark applications filed in all countries foreign to the United States.

MUNN & Co.,
Patent Solicitors,
233 Broadway,
New York, N. Y.

Branch Office:
625 F Street, N. W.,
Washington, D. C.

Table of Contents

	PAGE
The Specificity of Proteins and Carbohydrates.—By E. T. Reichert	226
The Ignition of Explosive Gas Mixtures by Electric Sparks.—1 illustration	227
The King of Elephants.—By W. P. Pycraft.—5 illustrations	228
A New Use for Sawdust	228
Artificial Camphor	228
The Washington Navy Yard Wind Tunnel.—3 illustrations	229
Vine Hedges	229
Food Selection.—II.—By C. F. Langworthy	230
Ancient Principles of Physiognomy	231
A Museum Becomes the Seat of Government.—By Harlan I. Smith.—3 illustrations	232
The Utilization of Peat	233
War Brings Prosperity to the Cutlers	233
Salts, Soil-Colloids and Soils.—By L. T. Sharp	234
The Surface Tension at the Interface Between Two Liquids.—By W. D. Harkins.—1 illustration	235
Making Wild Animals Take Their Own Pictures.—By William Nesbit.—19 illustrations	236
A Reagent for Etching Mild Steel	238
The Simplex Calendar.—A Correction	238
"Ghost Lines."—By J. O. Arnold	239
How Stone Is Sold	240

³ See important note in appendix.