GHOST LINES IN STEEL FORGINGS

Their General Appearance.—When a large forging is being turned in a lathe or machined by a shaper, etc., it not infrequently happens that a careful inspection will reveal faint lines which run parallel to the length of the forging and show up with a whitish tint against the grey of the mass of steel. These lines may be quite short, such as an eighth of an inch or they may be many feet long, running conceivably the whole length of the forging. They are often best visible in the semi-finished or even rough-machined state, being usually lost in finish water cuts unless very gross. Their width may vary but a width of a thirty-second or a sixteenth of an inch is common.

They may appear and disappear as machining proceeds, alternatively they may not do so as will be seen later. Such lines are called "ghost lines" or simply "ghosts," which is an expression best taken to include all white lines or bands which appear on machining a forging.

What they Are.—Ghosts should be regarded as examples of very marked local heterogeneity. They are usually associated with a string of non-metallic inclusions.

They should not be confused with micro-banding (a fine banding which is almost universal in rolled mild steel, and is normally only visible under the microscope), although even this is, as regards size, a function of size of ingot and, therefore, in very large ingots may be visible to the naked eye and become of importance. Ghosts may be of the form of a thread or of a plate or lamination.

White lines or bands may appear on forgings owing to lack of carbon, excess of carbon or unequal distribution of carbon and such variations in carbon content may arise from unlike causes. White bands associated with sulphide segregates and also free from sulphide segregates may arise from similar causes.

In the un-annealed condition ghost lines usually contain percentages of carbon, silicon, manganese, sulphur and phosphorus in excess of the average, an analysis in one case giving results as follows:—

—	Area free from ghosts.	Ghost line.	Percentage increase.
Carbon	0·320	0·380	19
Silicon	0·080	0·310	287
Manganese	0·680	0·920	35
Sulphur	0·020	0·045	125
Phosphorus..	0·035	0·050	44

On annealing the carbonised ghost may become decarbonised, the austenite being expelled to the edges of the ghost line and the ghost is then a streak of iron free from carbon but containing in solid solution, and hence invisible under a microscope, 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-grey streaks of manganese sulphide.

On being machined the tool, on meeting the band boundary, partially jumps the ghost, showing it up relatively white against the grey of the mass of steel and in slight relief.

Their Types.—Ghost lines may be separated into three types produced by different effects, but in each case the result is segregation of the constituents of the steel, and it is these segregated areas that appear as ghosts.

The three types of ghost referred to above may be classified thus :—

(1) Those due to the " A " segregate in the ingot ;
(2) Those due to corner segregation in the ingot.
(3) Those due to blow-holes in the ingot.

Their Detailed Properties.—The " A " segregate ghost rusts at an accelerated rate and makes a corresponding dark line on a sulphur print. It is always associated with sulphide segregates and these in turn are formed only in ingot material and therefore can only be controlled by the ingot maker. " A " segregate ghosts consist of strings in the forging, and, therefore, appear and disappear as machining proceeds. Their length will depend upon the relation of the plane of the ghost to that of the machined surface, the whole of the ghost being visible if these planes coincide while alternatively only a spot will be visible if the plane of machining cuts the line of the ghost at right angles.

Owing to their origin it will be evident that " A " segregate ghosts will be in a cone with axis coinciding with that of the ingot ; therefore the ghosts may appear anywhere or everywhere on the circumference of a forging such as a shaft which is turned in a lathe between centres coinciding with the axis of the ingot, but as the " A " segregate never extends to the outside of an ingot it follows that these ghosts will not appear until a certain thickness of the outside of the forging has been machined away.

The corner-segregate ghost is due to corner segregation in an angular (not round) ingot, and in consequence is part of a *plane* of segregation and not a thread or string only. Hence it will *not* disappear as machining proceeds until the whole of the corner segregate has been machined away. Further, being part of a plane, the ghost may be of very considerable length, conceivably extending, in an extreme case, the whole length of the forging.

As corner-segregate ghosts are associated solely with the corners of the mould in which the ingot was made it follows that there can only be the same number of ghosts in say a turned shaft as the number of corners in its ingot—usually eight. Further these ghosts will be approximately equally spaced around the shaft, and this is a valuable clue in deciding what the particular type of ghost is.

Since corner-segregation extends practically to the outside of an ingot it follows that the corresponding ghost may appear as soon as machining is commenced.

The blow-hole ghost is produced by drawing out during forging an originally more or less globular blow-hole and therefore is of limited length.

Their Causes.—*The " A " segregate ghost* is probably the most commonly met with, and is actually the " A " segregation of the ingot. For its origin reference should be made to text books on the subject of ingot structure, but briefly it is as follows. When an ingot is cast in a chill mould (*i.e.*, made of cast-iron or cast steel) the first process is that the molten metal swirls up the sides of the cold mould, and instantly freezes to form what is called the swirl envelope. The steel now commences to freeze steadily inwards from the swirl envelope, and does so by forming crystals whose axes are roughly at right angles to the wall of the mould. These crystals are called chill crystals and exhibit during their growth, what is called selective freezing, being rich in iron and pushing in front of them as they freeze a mixture which in consequence, is rich in the other constituents of steel, viz., carbon, silicon, manganese, sulphur and phosphorus, together with any slag and dirt which may have been in the steel when teemed (*i.e.*, poured from the ladle into the mould). Presently these chill crystals cease to form, very possibly because the outer frozen portion of the ingot breaks away from the interior surface of the mould on account of shrinkage and thereby causes heat insulation by a layer of air between ingot and mould.

The steel now crystallises in a promiscuous manner, producing non-orientated crystals and at the inner boundary of the chill crystals centres of segregate (*i.e.*, portions of steel rich in carbon, silicon, manganese, sulphur and phosphorus) now form as globules. These globules have a lower specific gravity than steel, and, therefore, tend to float upwards through the viscous semi-fluid steel, leaving behind a trail which is the ghost in the finally frozen ingot. Thus the " A " segregate ghosts are already strings before forging commences, but the operation of forging draws them out still further.

It appears that sulphur is a predominant factor in the formation of the " A " segregate, and that just before the ingot solidifies a definite alloy of iron with manganese sulphide freezes out from solution and segregates to a series of centres. These frozen masses seem to act as nuclei around which gather the elements carbon, sulphur, phosphorus, and (if present) nickel.

" A " segregate ghosts are almost invariably absent in ingots of one ton or less, but generally present in ingots of two tons or more.

The distance of the " A " segregate from the wall of the mould depends upon the temperature at which the steel is cast, and also upon the amount of chill, *e.g.*, whether cast in sand or in iron moulds.

The corner segregate ghost is met with in large straight carbon steel ingots and forgings, and in even small ingots and forgings of alloy steel. They are due to the entrapping of segregate between adjacent walls of chill crystals which, owing to their selective method of freezing, push the segregate in front of them as they freeze.

A study of Fig. 1 will make the matter clear and it will be observed that the corner segregate commences practically at the outside of the ingot, extends the length of the chill crystals and ceases when the non-orientated crystals begin to form.

It will be evident that if the mould were a round one there would be no corner segregation, but difficulties are experienced with round ingots, and they are not very frequently used, hexagonal or octagonal being usually preferred. The segregate in this case is obviously a *plane* instead of a string, and its length may extend practically the whole length of the ingot. It will, therefore, be clear that this form of segregate is a far more potentially dangerous one than the " A " segregate.

The blow-hole ghost is simply the result of drawing out a blow-hole during forging. Blow-holes are liable to form during the freezing of an ingot owing to the absorption of gases by liquid steel and its subsequent expulsion on freezing. Blow-holes are usually associated with segregates and when the ingot is forged or rolled those segregates are drawn out into bands or threads which may be difficult to distinguish from the " A " segregate ghost, though they are usually smaller, richer in impurities, and have more sharply defined outlines.

From the method of their formation it will be evident that the length of each ghost is limited.

How to Examine Them.—The first thing to do when examining a forging which exhibits ghost lines is to ascertain which of the three types they represent since the corner segregate ghost, being a plane instead of a thread, is obviously far more potentially dangerous than the other two. The best way to set about this is to take a sulphur print of an end section ; this will reveal the ring of " A " segregate and, if present, the corner segregate, and by comparing the positions of these features with those of the ghosts under consideration it should be possible to form a very good idea of the type of ghost which is being dealt with. By ascertaining the number of corners in the mould in which the ingot was cast it should be easy to check corner segregation, since this will be more or less evenly spaced round the periphery of the forging and the ghosts will correspond in number to the number of corners in the mould.

It may be difficult to distinguish a blow-hole ghost from an " A " segregate ghost if the former lies within the " A " segregate

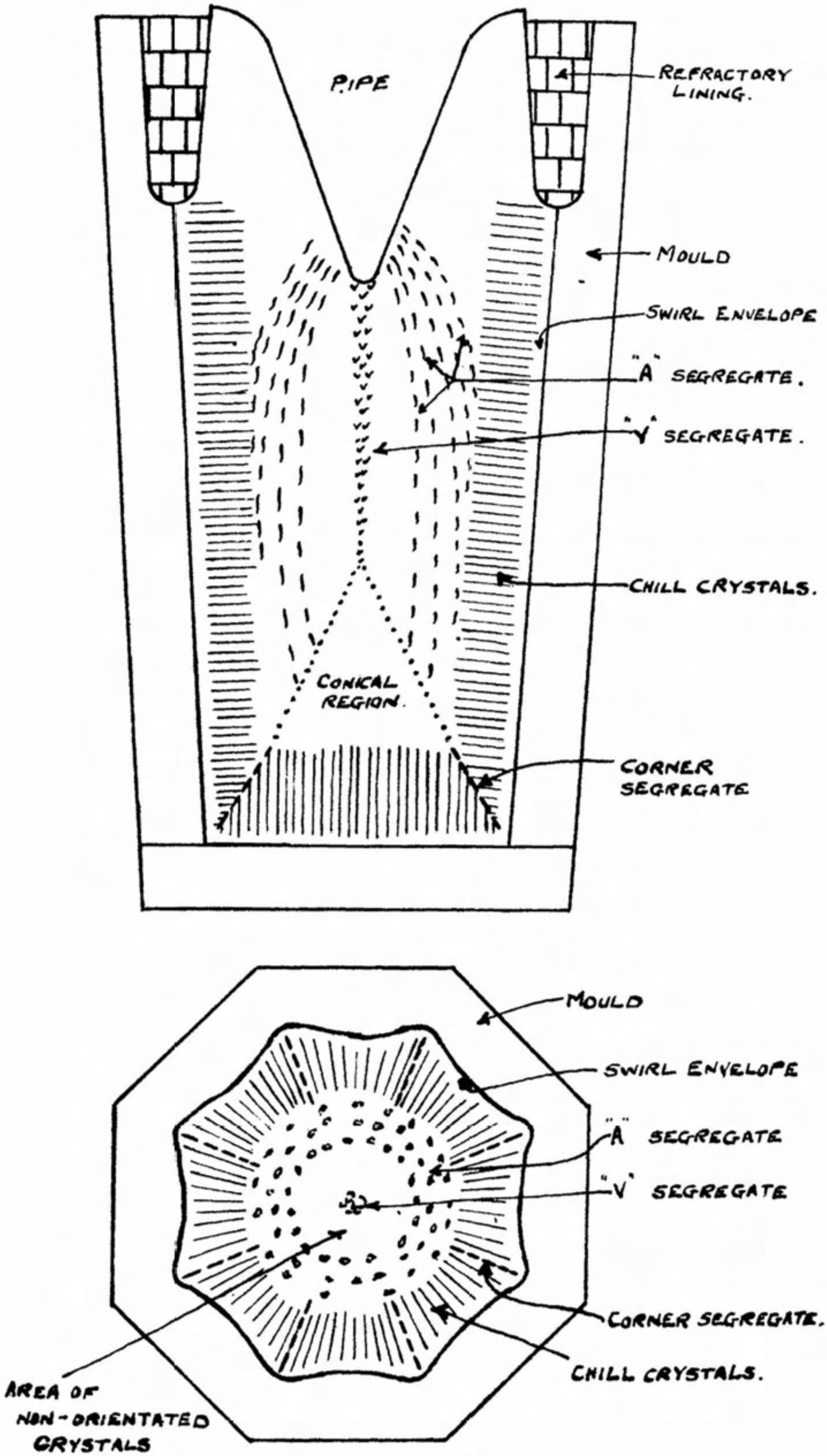
PIPE
REFRACTORY LINING.
MOULD
SWIRL ENVELOPE
"A" SEGREGATE.
"V" SEGREGATE.
CHILL CRYSTALS.
CONICAL REGION.
CORNER SEGREGATE
MOULD
SWIRL ENVELOPE
"A" SEGREGATE
"V" SEGREGATE
CORNER SEGREGATE.
CHILL CRYSTALS.
AREA OF NON-ORIENTATED CRYSTALS

FIGURE 1.

area, but if a mistake is made here it does not very much matter.

In making use of the cross-section sulphur print for locating the "A" segregate zone it must be remembered that the latter is a hollow truncated cone with a small apex angle, and is not a cylinder.

If difficulty is experienced in locating ghost lines or ascertaining exactly where they end a sulphur-print can be taken or the forging etched; either of these methods, but particularly the sulphur print, will reveal the exact location and extent of any ghost. In severe cases, however, the naked eye is quite sufficient for this purpose.

Having decided which type of ghost is being dealt with some effort must be made to ascertain of what mechanical importance they are. From their very nature ghosts are undoubtedly places of potential weakness, but experience indicates that they may vary through all the degrees from practical harmlessness to very serious danger. To take the worst case first, there may be actual separation at the ghost, *i.e.*, a crack running through the centre of it; this will be best shown up by a microscopic examination after etching which will reveal a crack if one exists. Another delicate method of detecting separation is to make use of the magnetic test.

This test can best be carried out in the laboratory and is only applicable to cases where the shape of the piece to be tested is suitable, *i.e.*, it should preferably have a comparatively flat surface.

The method of application is as follows:—

The piece of steel to be tested is smooth machined and temporarily magnetised by placing it as a keeper across the poles of a powerful horse-shoe electro-magnet, the steel being preferably so positioned on the poles of the magnet that the magnetic lines of force will be approximately at right angles to the line of any crack that may exist. As these cracks invariably lie in a plane containing the axis of the forging, this means that the magnetic lines of force should be arranged at right angles to the axis of the forging (*see* Fig. 2).

A very fine iron powder is now taken which is ground to the consistency of jewellers rouge (*i.e.*, to the smallest practicable size of grain), and is mixed with alcohol or methylated spirit in which a considerable proportion of the iron dust remains suspended. This mixture is then made to flow slowly over the magnetised flat surface, and presently the magnetic lines of force will be found to be beautifully traced out by the iron powder.

Should any metallic discontinuity exist in the surface of the material such as would be produced by a hair crack, even though quite invisible to the naked eye, and possibly also under a magnifying glass, the resultant breakage of the lines of force will cause north and south poles to be formed at the edges of the crack; these poles will attract the adjacent particles of iron powder with the result that the crack becomes clearly visible as a black line of iron powder.

If a crack exists in a ghost very thin ribbon shavings removed by a flat turning tool in a lathe will break as the cutter passes over the ghost line.

If there is no actual separation there is no way of deciding on the weakness of a ghost line except by means of mechanical tests, and these can only be carried out if surplus material is available. If the forging is finish-machined or nearly so it may be possible to apply tests to the material discarded from the ends of the ingot provided such material contains similar ghosts. In view of the limited area of the " A " and blow-hole ghosts a tensile test is obviously of little value, but the following can be applied in order to get some idea of the weakness of the ghost :—

(*a*) A bend test with the ghost running along the line of maximum tension, thus :—

(*b*) An Izod impact test, making the specimen of dimensions 10 mm. × 8 mm. instead of the usual 10 mm. × 10 mm. with 2 mm. notch, and arranging the ghost to lie where the bottom of the notch would normally be.

(*c*) A torsion test whereby a rod of the material containing a ghost on its surface is tested to destruction by twisting and observation made as to whether failure occurs along the ghost line.

For purposes of comparison it will be desirable to make similar tests with material from the same forging which is free from ghost lines.

Probably the most valuable of these is the Izod test, since this tends more than the others to exaggerate the importance of the ghost line.

When examining ghosts it should be recollected that they are frequenlly associated with non-metallic inclusions, *e.g.*, small particles of slag, and the importance of this will be realized when it is remembered that the ghost itself is after all a kind of steel though perhaps of very poor quality while the non-metallic inclusion is a foreign body in no way related to steel as a metal, and, therefore, its presence necessarily involves a definite discontinuity in the steel. Such inclusions will be seen under a magnifying glass as a blackish spot which is usually of the shape of the externally visible portion of a human eye.

A word of caution should be added as regards the interpretation of a sulphur print of ghost lines, and that is that there is no relation

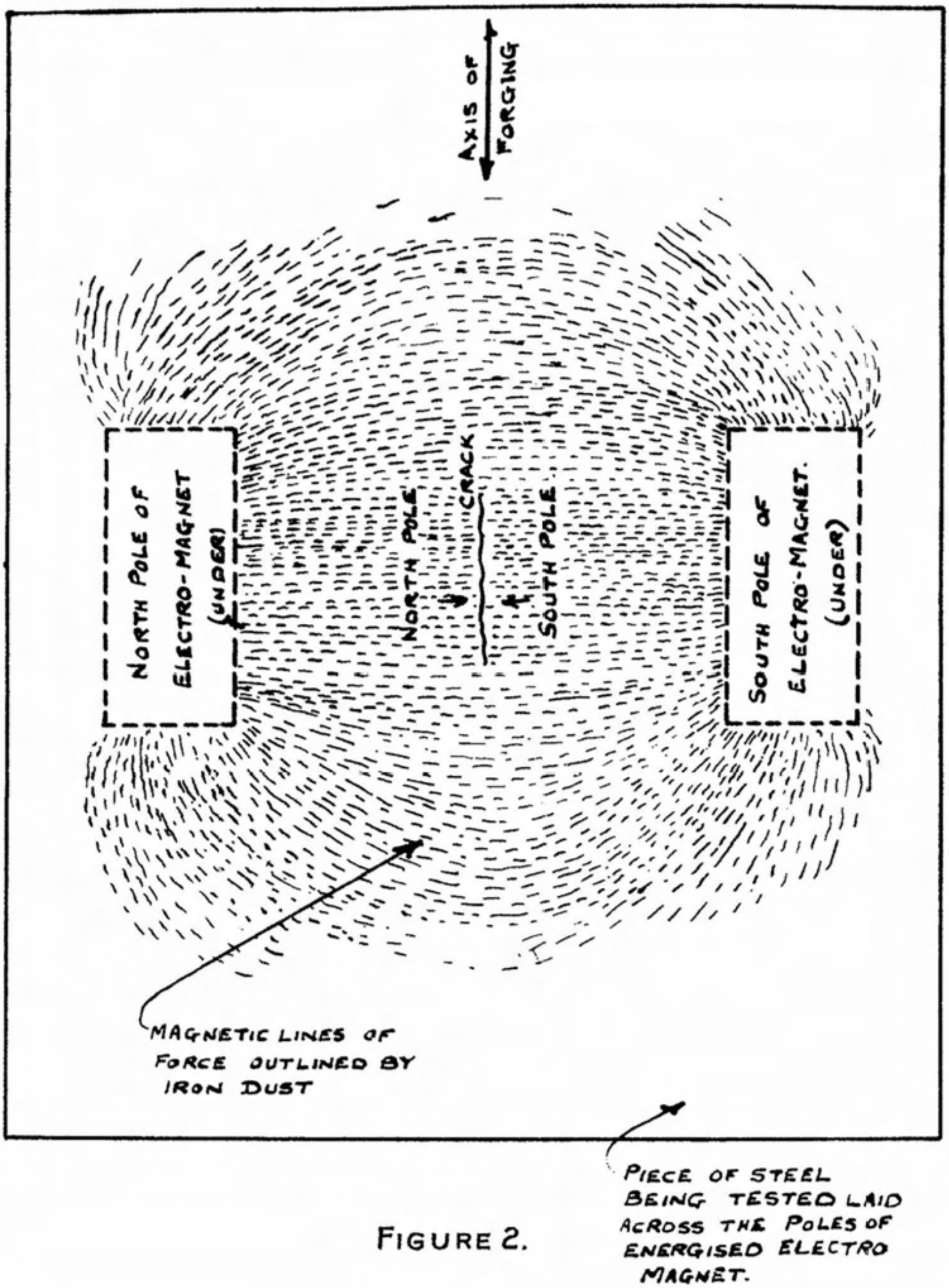

FIGURE 2.

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whatever between the appearance of the ghost on the sulphur print and its physical properties, *i.e.*, the sulphur print must be used for no other purpose than to locate the ghost. Ghost lines will be found which will give a very black sulphur print and yet be practically harmless, whereas, on the contrary, many corner ghosts have been found which are invisible to the naked eye, show the barest of marks on the sulphur print, and yet on testing by means of a bend test have been found to be highly dangerous.

Their Importance.—In considering the relative harmfulness of ghosts it is necessary to take into account certain facts.

Firstly, ghosts must be of less importance in a very soft and ductile steel which by slight local yielding can bring about a uniform distribution of loading which can never be obtained in a harder steel where ghosts are therefore liable to be very serious in setting up local internal stresses.

Secondly, ghosts usually run longitudinally along the ingot or forging, and, therefore, may be of no great moment where only longitudinal or torsional stresses are involved, *e.g.*, propeller shafting.

Thirdly, where shock, and more especially fatigue, has to be resisted, and where stresses of serious magnitude transverse to the direction of rolling or forging are involved the avoidance of ghosts becomes a matter of importance. An example of this will be a gun tube.

If ghost lines prove to be the result of corner segregation then they should evidently be treated with far greater suspicion than those belonging to the " A " segregate and blow-holes, and the results of tests obtained interpreted accordingly.

If they consist of segregates only without non-metallic inclusions it is quite possible that any tests made will prove satisfactory, and the material will be little the worse for the presence of the ghost lines.

If, on the other hand, non-metallic inclusions are present in any quantity then the strength of the material will be affected, and it must be regarded with grave suspicion.

Professor J. A. Arnold examined a tail shaft forged from the lower end of an 80-ton ingot, and containing moderately large ghost lines. He applied tension, torsion and alternating tests, and found no signs of cracking or opening due to the ghost lines. He was therefore of the opinion that no risk was involved by putting similar shafts to the one under examination into vessels building.

Summing up it seems probable that the normally-met-with ghost lines consisting of " A " segregate are usually 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, *e.g.*, a rod or shaft in tension, torsion or other alternating stresses, and there are few or no non-metallic inclusions. Similar remarks apply to blow-hole ghosts, but corner segregation must be regarded with much greater suspicion.

In the case of ghost lines on journals for bearings it must be recollected that ghosts are usually very slightly raised above the surrounding metal, and that the ghost is a different type of steel from the remainder. Hence there is the possibility of trouble both from a wearing and a corrosion point of view, but of this little is known.

Finally, it must be recollected that ghost lines can never be eradicated from large masses of forged steel until metallurgical science has entirely eliminated sulphur from steel.