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R. Halmshaw

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The present role of radiological methods in engineering

By R. Halmshaw
AP4 Branch, R.A.R.D.E., Ministry of Defence, Fort Halstead, Sevenoaks, Kent, U.K.

A brief outline of the history of industrial radiology is given.

Major applications are radiography-on-film applied to flaw detection in weldments and castings and to ordnance inspection. Techniques almost invariably use metal intensifying screens, as distinct from salt screens, so that modulation transfer function values of 30 lines/mm at 10 % modulation are easily obtainable. To cover the range of metals and metal thicknesses used in engineering, X-ray energies from 20 keV to 30 MeV are used, as well as gamma-rays and neutrons.

Radiography has some serious limitations for flaw detection, and ultrasonic testing has replaced it in some applications, but radiography has several very important factors in its favour, which are detailed.

The industrial use of non-film techniques, such as fluoroscopy in its various forms, is discussed; usually a compromise has to be made between having a poorer detail sensitivity than on film, and a cheaper or speedier inspection.

The methods of specifying detail sensitivity in industrial radiography are briefly mentioned.

1. Introduction

Engineering materials are not always what they seem. Cast metal can look perfect on its machined external surfaces yet contain large internal cavities which cause rupture under stress; welds can contain internal cracks and even wood can contain large regions of internal rot with no external evidence of the extent of the damage. As soon as engineering materials were used under stressed conditions, occasional failures occurred, and X-rays were recognized as a potential method of finding internal defects in metals almost as soon as they were discovered in 1895. It was not until 1919, however, that industrial radiography was taken seriously, because the very short wavelength X-rays required to penetrate useful thicknesses of metal could not be generated. Describing X-rays by the voltage required across the X-ray tube, medical diagnostic X-rays are in the 50–120 kV range, whereas an industrial radiographer uses 40–200 kV X-rays for aluminium alloys, 150–300 kV X-rays for ferrous metals, and up to 20 MV X-rays for large cast steel and very thick weldments.

The bulk of industrial radiography is done on light-alloy materials, e.g. aircraft components, on steel from 10 to 40 mm thick (welds, castings), and on ordnance components; X-rays up to 300 kV are adequate for much of this work. Reliable equipment in this range became readily available just before World War II and has developed slowly but steadily since.

High-energy linear electron accelerators are used for industrial radiography in the energy range 4–20 MeV, to produce X-rays which can penetrate steel up to 400 mm thick.

2. Techniques

Most industrial radiography involves placing a source of radiation on one side of the specimen, a film in a cassette on the other side, choosing an appropriate X-ray energy and exposure time, exposing and then developing the film, and then looking at it. It is not necessary to keep the radiation dose to the specimen to a minimum as in medical diagnostic radiography, and it was soon discovered that much better image detail could be obtained by discarding the fluorescent intensifying screens used by medical radiographers and exposing the film between metal intensifying screens, generally thin lead foil. To keep the exposure times short (typically, less than 5 minutes) a higher X-ray voltage was used but this in fact generally reduced the problem of scattered radiation and improved the radiographs: film manufacturers have produced special films for use with metal screens and these have a higher contrast than medical radiographic films; also, the contrast continues to increase with film density up to densities greater than 10–12 (way beyond the viewable region!), so typical good industrial radiographs have film densities between 2.0 and 3.0. Industrial radiographs taken with X-rays below 200 kV should have image detail corresponding to modulation transfer function values of 40 lines/mm at 10 % modulation, compared with 8 lines/mm on a typical medical radiograph taken on salt intensifying screens. Even using very high energy X-rays or gamma-rays we expect to get 4 lines/mm resolution (figure 1).

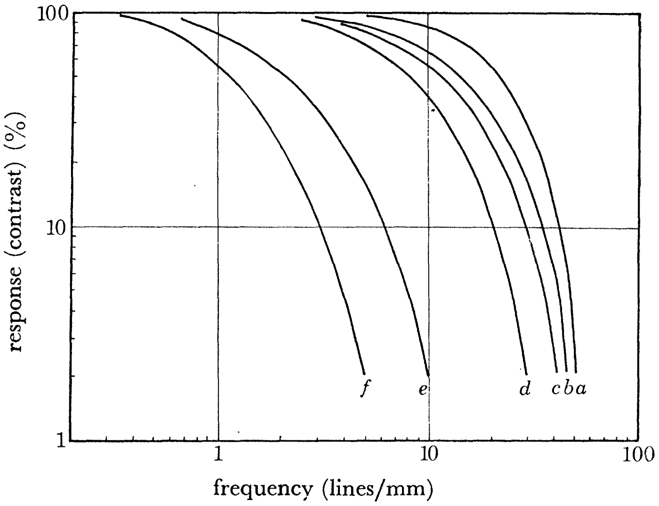

FIGURE 1. Experimental curves of modulation transfer function for a fine-grain radiographic film exposed to filtered X-ray beams of various energies. Curve (*a*), X-rays of 70 kV; (*b*) 200 kV; (*c*) 300 kV; (*d*) 400 kV; (*e*) 1 MV; (*f*) 5.5 MV.

Quite a lot of industrial radiography is done with gamma-rays, with the use predominantly of two radioisotopes, iridium-192 and cobalt-60. Gamma-rays are used because one can produce adequate radiographs of steel from 20 to 100 mm thick with relatively cheap, simple equipment; the use of X-rays requires large, expensive and cumbersome equipment needing power supplies and often water cooling as well, which is not very convenient on site work in such places as shipyards or steel foundries. A typical gamma-ray source is about 20 Ci and a modern gamma-ray equipment uses a method of pushing the source, by means of a flexible cable in a tube, from a storage container to a 'collimating head' previously erected at the exposure site. A radioisotope source with a radiation emission capable of producing good radiographs on thinner sections would be very useful, but there is nothing very suitable in terms of suitable gamma-ray spectrum, half-life and specific activity; thulium-170 and ytterbium-169 are used on a very limited scale. In the U.S.A. a neutron-emitting source, californium-252, is being proposed for use in a similar type of container, for neutron radiography on site, but this is a very expensive installation and none are yet in use in Europe.

2.1. *Image quality*

A radiographic image on film is the projection of the specimen on to the two-dimensional plane of the film and is, within close limits, the same size as the specimen. Geometric conditions are usually adjusted so that the image is not blurred by the effects of the source diameter, so that the sharpness of the image is generally controlled by electron spread in the film emulsion. The contrast of the image is controlled by the radiation energy and the film contrast gradient; the latter can be of the order of 4–6 and this gives film an enormous advantage over any other radiation recording system. The number of X-ray quanta utilized in producing unit area of image sometimes also causes a limit to the image detail – the so-called 'quantum mottle' or 'quantum fluctuation noise'. This is particularly noticeable with high energy X-rays and gamma-rays – as also with medical radiographs – but is not, usually, the limiting factor on image detail on most industrial radiographs.

On a good radiograph one expects to detect a thickness change of about $\frac{1}{2}$–1 % of the specimen thickness irrespective of the total thickness, but the specification of defect sensitivity is much more complex as it depends on the width and orientation of the defect as well as on its 'through-thickness' dimension. In engineering, the crack is usually considered to be the most potentially serious defect in stressed structures and radiographic crack sensitivity is a complex function of crack and radiographic techniques parameters.

A 'tight' crack, i.e. one with a separation of the crack faces less than 0.02 mm, is unlikely to be detected by radiography unless the crack plane and the radiation beam happen to be within a few degrees of one another, and this constitutes the chief limitation of radiography as a defect-detection technique. In stressed structures if the material is brittle, even the smallest crack can propagate rapidly under stress, and so must be detected.

3. ADVANTAGES AND LIMITATIONS

The present case for using industrial radiography can therefore be summarized:

(1) A radiological examination can be done on any material irrespective of its grain size or composition, on specimen thicknesses from 0.5 to 400 mm steel or its equivalent. In particular, austenitic steels and copper alloys, which give serious problems with ultrasonic testing, can be radiographed without difficulty. The radiograph can always be sharp and clear if the operator is skilled and has suitable equipment, as there is no restriction on exposure time except economics and no problems with patient dosage or movement.

(2) The reliability of defect detection depends on the nature and orientation of the defects; volume-type defects such as cavities or porosity are easily detected and identified down to a size equivalent to about 1 % of the total thickness; planar defects are detected only if their orientation is favourable; randomly orientated planar defects can only be detected with certainty if several radiographs are taken at different angles.

(3) An image on film is obtained, which is a permanent record; if film viewing conditions are adequate, interpretation of the defects in terms of their nature and two of their three dimensions is normally easy; superimposed images of defects at different depths in the specimen are rarely difficult to interpret.

(4) The use of radiography for checking assemblies, fillings, measuring internal dimensions, are other important applications, quite distinct from, and sometimes more satisfactory than, defect detection in welds and castings. Measurements are often possible to an accuracy of ± 0.02 mm.

The disadvantages of radiography in non-destructive testings are:

(1) The inability to detect fine planar defects such as cracks with certainty.

(2) The inability to measure the 'through-thickness' dimension of a defect, particularly of a planar defect.

(3) The very high cost of high-energy X-ray equipment suitable for the inspection of steel of thickness greater than 150 mm.

4. Present status in relation to ultrasonic testing

An E.E.C. assessment made in 1976 (Röper & Kaempf 1976) showed that radiography (X and gamma) had 36% of the non-destructive testing market and ultrasonics 33%. The comparable figures for 1971 were 48 and 23.5% respectively. Extending these forecasts to 1985, the figures suggested were: radiography 26% and ultrasonics 32%. These figures are based primarily on equipment sales, and in view of the long life of commercial X-ray equipment and the slow change in equipment design, they are probably pessimistic in terms of the total use of radiography in industry.

Basically, in comparing radiography and ultrasonic testing for defect detection, we are attempting to compare two fundamentally different techniques. In radiography one has an image on film: it looks like the specimen; one can examine it at leisure; one can get a second opinion if necessary; most industrial radiographs are sharp and clear and, provided one understands the metallurgy or construction of the specimen, interpretation is rarely difficult. The limitations of radiography for defect detection are, however, very real – from any study of materials science and fracture mechanics, the critical defect is the crack which can propagate to catastrophic failure: cracks can be 'open' or 'tight' and occur at any angle, and it is tight, angled cracks which are the most difficult defects to detect by radiography. Ultrasonic testing, as done today in industry, is, however, not by any means the perfect replacement for radiography. The ability to detect a crack with ultrasonics does not depend on the crack width (opening), so in theory very tight cracks can be detected, but it does depend on crack angle and also very very much on operator skill. Interpretation of the ultrasonic signals is not easy, nor is defect size measurement; there is often no permanent record, so that one is almost entirely dependent on the skill, consistency and conscientiousness of the individual operator.

Signal recording, data processing and data recording might change all this in the future, but at present the aim of much data processing in ultrasonic inspection seems to be to make the result look like a crude radiograph! I believe, as in the E.E.C. survey mentioned earlier, that ultrasonic testing, as it continues to develop, will continue to replace some radiographic applications, but it would be wrong to regard radiography on film as a dying technique.

There is a more general limitation to non-destructive testing which is not limited to either radiographic or ultrasonic testing. This is, that once one has identified a defect in a metal or other material, one still has to determine its significance: can it be left alone, or must it be repaired? How long will the structure last? In a few materials and in a few simple cases where stress distributions and working-life stress levels are known, fracture mechanics will give determinations of critical defect size, but in most engineering applications the acceptance and rejection of defects found by non-destructive testing is still an arbitrary process, often left to rather vague codes of defect acceptance.

I suppose there is an analogy in the medical situation in that if one shows a broken bone there is no problem of leaving it alone, but if a radiograph shows small gall-stones, one has a problem of whether to 'repair' or not. In the medical world, decision-making is more organized and this decision would be the province of a qualified medical man, not the radiographer; in industry this distinction is less clear cut.

5. Fluoroscopy

Radiography on film is by far the most widely used technique, but fluoroscopy, image intensifiers and television fluoroscopy have found limited use in industry; their lack of use is partly because to get good results very expensive equipment is necessary, and partly because the results, when compared with film, always seem to be poor in image quality by comparison. In non-destructive testing the inspector does not usually know the minimum size of defect which he needs to find, so he tends to insist on using the most sensitive technique, which is film, and there are only a few routine applications of television fluoroscopy where the poorer detail sensitivity has been accepted because of the saving in film costs and time; one of the most important applications is to the inspection of vehicle tyres.

Because most industrial radiology needs X-rays of 150 kV or more, the primary conversion screen in any fluoroscopic system or image intensifier has a very low efficiency of conversion of X-rays, and image detail is limited by quantum fluctuation mottle; flaw sensitivities are usually poorer than on film by a factor of 2–3. The latest caesium iodide screen image intensifiers have given some improvement in performance in this respect, but even these are designed primarily for medical energy X-rays. Unfortunately it is with low-energy X-rays where fluoroscopy systems compare least favourably with the very fine detail which can be recorded on film.

The problem of quantum mottle limitations could be overcome by image time integration but this would be expensive and complicated and has not yet progressed beyond the research laboratory. Cine-television fluoroscopy is used by a few research laboratories but there are no widespread applications as there are in the medical field.

6. Neutron radiography

The use of thermal and cold neutrons generated in atomic reactors for radiography has shown that this could be an important new field of application. Most of the work has been done in the U.S.A. and in France, and in this country there is a lack of suitable high-intensity thermal neutron sources. The special properties of thermal neutrons which makes them of interest is that their absorption characteristics are very different from X-rays. Particular elements – hydrogen, gadolinium, cadmium, indium – absorb thermal neutrons very strongly, whereas dense metals such as steel and lead are not strong absorbers. This means that neutron radiography can be used to show hydrogenous material of low physical density inside metal structures: paper washers, plastic components, explosive fillings, oil, water, etc. Also, liquids can be loaded with highly absorbing salts such as gadolinium nitrate to make them show even more clearly. Cold neutrons produce in addition an edge-enhancement effect on radiographs, which increases the discernibility of image detail. Neutron radiography would be a very important new technique if practical sources of thermal or cold neutrons were available: at present, to get good-quality radiographs, specimens have to be taken to an atomic reactor where a suitable neutron port is available.

7. Conclusions

In industrial radiography we can produce films of much better image quality than conventional medical radiographs. We can use a wide range of X-ray energies, filters, special films and screens, variation in processing, long exposure times, etc., and can obtain either high contrast or wide thickness latitude (or sometimes both), together with very good resolution, but none of these advanced techniques are much used in medical diagnostic radiography, because of the constraints of minimum patient dose and patient movement.

I have sometimes wondered whether or not we really need the very high image resolution, but I meet occasional cases of very small fine cracks being revealed by good radiography, whereas poor radiographs would either not show these cracks at all, or cause difficulties in interpreting them as cracks. In my particular field we meet more and more cases where it is desirable to use a very fine-grain single emulsion film and to use a low-power magnifier to look at the images.

If we employed the very high-speed salt intensifying screens which are used in medical radiography, we could use a lower X-ray energy to examine any given specimen thickness and this would give an increase in image contrast at the expense of a loss in image sharpness. Detail sensitivity depends on both contrast and sharpness and every ten years or so the argument as to which is more important is reopened. I believe I know the answers within my own range of applications and I never use salt intensifying screens, but it could be a point worth discussing.

On fluoroscopy and its derivations, we have nothing to offer the medical people; our equipment is derived directly from theirs.

On film viewing, we have our own special problem of getting viewing screens suitable for the higher film densities which we like to use. We can never get as much light as is desirable.

On film interpretation, I think perhaps we can learn from the medical people. I wish we had more qualified radiographic interpreters with the necessary engineering knowledge to understand the significance of what they see on a radiograph. We tend to fall between the two stools of letting the radiographer 'read' the film with inadequate knowledge of the significance of defects, and bringing in a designer who knows slightly more about defects but who has little experience in reading a radiograph.

Reference (Halmshaw)

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