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Autor: Berthold, R.

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Testing of Welds.

Prüfung der Schweißnähte.

Contrôle des soudures.

R. Berthold,
Leiter der Röntgenstelle beim Staatlichen Materialprüfungsamt, Berlin-Dahlem.

The further progress attained in the testing of weld seams since the First International Congress of the International Association for Bridge and Structural Engineering has been marked by two main developments: the application of fatigue tests and the introduction of non-destructive methods of testing, especially the use of X-rays. An essential connection exists between these two developments.

A) Fatigue tests.

So far as statical tests are concerned — the tensile test, the folding test and the notching test — accepted principles and standards governing the shape and dimensions of the test bars and testing arrangements now exist in many countries, including Germany. As regards fatigue tests, however, conventions of this kind are still largely lacking. In Germany there is only DIN 4001, which, in the first place, standardises the nomenclature of fatigue testing, and in the second place defines the limiting alternating stress of steel as being that stress which the test bar will withstand during two million applications of load.

Apart from this standard there are the regulations of the Reichsbahn (German State Railways) for welded plateweb girders, in which certain alternating stress values are laid down for test bars of St 37 and St 52 of prescribed measurements and shape, both in the finished and in the unworked condition, applicable both to transverse and longitudinal welds. For instance, in the case of unworked transverse weld seams of Steel 37 or Steel 52, the prescribed alternating stress values are 15 and 16 kg/mm² respectively, while for tooled welds the corresponding values are 18 & 19 kg/mm². Whether these Railway regulations will be made into "DIN"-standards having general validity, has not yet been decided.

Other testing regulations in reference to fatigue tests are still in the preparatory stage.

It has been shown by experiments on fatigue tests that the strength values obtained from specimen welds under static loading cannot be taken as evidence of the fatigue strengths of the specimens, still less, therefore, of those of actual structures. Hence Thum, in his "Richtlinien für die konstruktive Durchbildung geschweißter Maschinenteile" (Principles for the design of welded machine parts) — not yet published — declares that high values of breaking strength, elongation and notching tenacity offer no guarantee of fatigue resistance, because the material is stressed in a different way under repeated alternating loading and under steady loading. Elsewhere *Bierett* (1)[1] observes that the "notching effects" are of much greater importance than the properties of the weld metal in determining the fatigue strength of a welded connection.

These statements are consistent with the fact that failure under repeated alternating stress always originates at the point where the concentration of stress is greatest. In other words, such defects as slag inclusions, imperfect roots, imperfect binding, bulges in transitions, pores, etc., which are of no great importance under static loading, become of decisive importance as regards the fatigue resistance of a welded connection.

The recognition of this fact disclosed an urgent need for some form of test that would allow the condition of the weld seam to be ascertained in the finished structure without causing damage.

In penetration by X-rays, a method which has been available for technical applications since about 1923, we have an expedient essentially well adapted for the non-destructive testing of welds.

B) The X-ray testing of weld seams.

1) *General principles.*

The general principles of X-ray penetration have repeatedly been described in engineering publications (2) and will, therefore, be taken as known.

2) *Testing with the fluorescent screen.*

The form of fluorescent screen now in use consists of a layer of zinc sulphide which becomes luminous to a greater or less extent according to the intensity of the X-rays impinging upon it. The experimental possibilities attainable by means of such a screen are, however, severely limited, because the fluorescence is not bright enough nor the definition sharp enough to allow of distinguishing slight differences in brightness; for instance, pores in a thickness of steel of 10 mm have to be at least 0.6 mm in diameter in order to be recognisable. This makes the detection of fine cracks and imperfect binding unreliable, so that the only suitable application of testing by means of the fluorescent screen is that which arises in the training of welders, whose work may be quickly examined by this means and bad flaws rendered visible immediately the welds are completed.

3) *X-ray photographs on X-ray film, with or without intensifying screen.*

The most promising means of examination is that offered by the use of double-coated X-ray film with or without an intensifying screen. Such screens consist of a calcium-tungstanate layer pressed on to each side of the X-ray film and rendered slightly luminous under the influence of the X-rays. Their use enables the period of exposure to be very considerably shortened, but at the same time there is some diminution in the sharpness of definition, and where the thickness of the material is slight, this notably impairs the quality of the

[1] See Bibliography.

picture. Experiments to determine the influence of intensifying screens on fault detecting power (4) have enabled suitable operating data to be obtained, which are reproduced in Fig. 1. These indicate that in order to secure maximum fault-detecting power thicknesses of steel up to 10 mm should be examined without such screens; those from 10 to 35 mm with sharply acting screens giving limited intensification; those above 35 mm with non-sharply acting screens giving high intensification.

The values of fault detecting power shown in Fig. 1 were measured by laying wires on the steel plate facing the side of the X-ray tube and photographing these together with the plate. Such values are not obtainable in the detection of

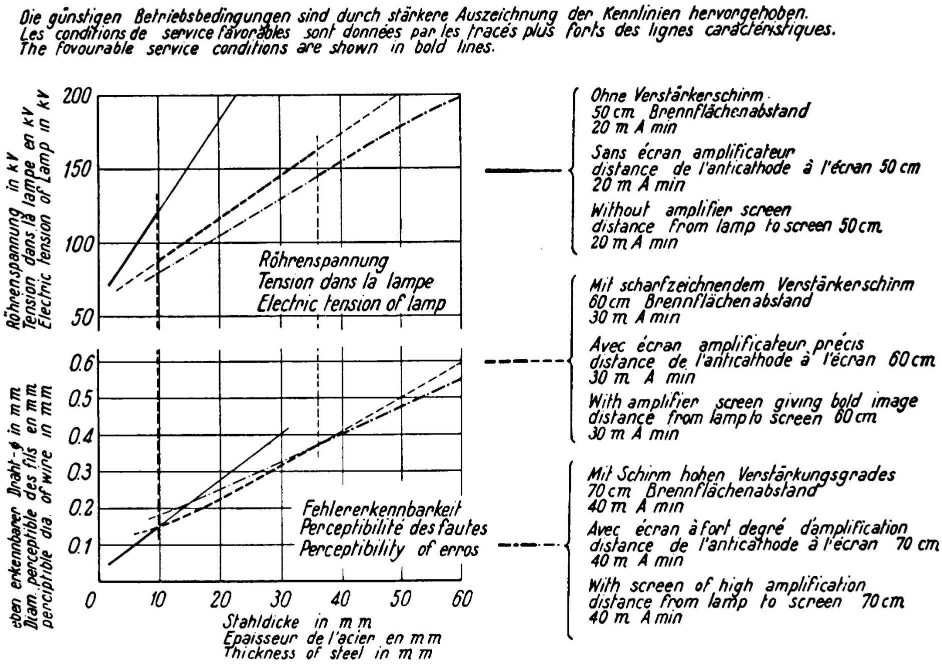


Fig. 1.

Practical data useful in X-raying steel.

cracks, because the dimensions of the activated surface in the X-ray tube are great enough to cause an overflow of radiation around the flaws, thus introducing penumbra and so reducing the contract of blackness on the film. In this way the detection of small cracks is subject to a limitation, especially where the X-rays do not happen to pass through such a crack in the direction of its greatest depth. Table 1 shows how the detectable width of crack is influenced by the angle between the X-rays and the direction of the crack:

Table I

Smallest width of crack detectable by means of X-rays, related to the angle between the direction of the crack and that of the rays. (Steel 40 mm thick; crack 6 mm deep.)

Angle, degrees	5	8	10	15	20	30	60	90
Width of crack, mm	0,03	0,06	0,09	0,13	0,16	0,21	0,32	0,40

A special difficulty arises in the examination of fillet welds in consequence of the varying thickness of metal presented in the direction of the rays. This difficulty can be overcome by placing a wedge of zinc over the fillet so that its varying thickness will counteract that of the cross section to be penetrated (5).

4) Standardisation.

When X-ray testing had so far developed that its use could be contemplated not only in scientific institutions but in the workshop, it became necessary to publish the "Code for the testing of weld seams with X-rays" *(Richtlinien für die Schweißnahtprüfung mit Röntgenstrahlen)*, numbered DIN 1914 and prepared by the German Association for the Testing of Technical Materials *(Deutscher Verband für die Materialprüfungen der Technik)* together with the welding technical committee of the *Verein Deutscher Ingenieure.* The object of this publication is to enable all X-ray units to produce photographs of uniform quality which can be interpreted in the same way, so as to establish the basis for a regulated procedure in operating. Among other provisions it is directed that a specimen consisting of wires of different diameters is to be laid over the welded seam and exposed to the rays together with the latter; it is required that wires of specified diameters, depending on the thickness of the plate shall then be recognisable. Table II contains particulars of the set of specimens adopted in Germany and Fig. 2 shows the X-ray photograph obtained from these.

Table II

Sets of wires adopted for control over quality of X-ray photographs in accordance with DIN 1914. (Each set, consisting of seven wires, is embedded in rubber.)

Material to be tested	Thickness of Specimen mm	Material and designation of set of wires	Diameters of wires in mm	Designation of sets of wires: Lead balls under wires	Colour of Rubber Sheath
Light metals	0 to 50	Al I	0.1/0.2/0.3 . . 0.7	● ●	grey
	50 „ 100	Al II	0.8/1.0/1.2 . . 2.0	● ●●	
	100 „ 150	Al III	1.5/2.0/2.5 . . 4.5	●● ●●●	
Iron Alloys	0 to 50	Fe I	0.1/0.2/0.3 . . 0.7	●● ●	black
	50 „ 100	Fe II	0.8/1.0/1.2 . . 2.0	●● ●●	
	100 „ 150	Fe III	1.5/2.0/2.5 . . 4.5	●●● ●●●	
Copper Alloys	0 to 50	Cu I	0.1/0.2/0.3 . . 0.7	●●● ●	red
	50 „ 100	Cu II	0.8/1.0/1.2 . . 2.0	●●● ●●	
	100 „ 150	Cu III	1.5/2.0/2.5 . . 4.5	●●● ●●●	

It was decided not to adopt the form of specimen prescribed in the American Boyler Code — consisting of a steel plate having grooves of different depths, or of a filter scale with drilled holes, placed close to the weld — since this does not enable the fault detecting power in the region of the weld itself to be ascertained.

The German Code also includes a series of provisions as to direction of rays, procedure to be followed in photographing, and aids to the testing of different sections of welds.

Conjointly with the drafting of this Code, *new dimensions for X-ray films* have been standardised by the aforementioned German Association for the Testing of Technical Materials together with the German X-Ray Society. The sizes hitherto in use are based on medical requirements and are not suitable for the examination of welds, each user being compelled to cut them himself to

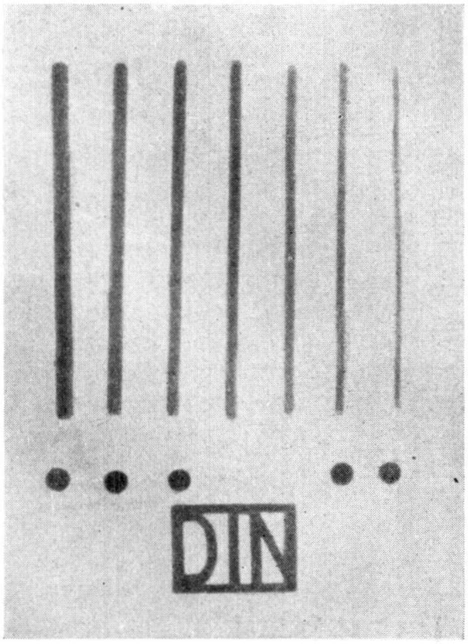


Fig. 2.
X-ray picture (positive) of wire screen Cu II.

sizes adapted to his needs. As a result of an agreement now reached between users of the process and makers of the films, intensifying sheets and boxes, the following film sizes have become commercially obtainable:

6 cm × 24 cm	10 cm × 24 cm
6 cm × 48 cm	10 cm × 48 cm
6 cm × 72 cm	10 cm × 72 cm

Regulations governing the construction of X-ray installations from the point of view of protection against danger from high intensity radiation have already been operative in Germany since 1929 and 1930 (DIN Rönt. 5 and 6); (6).

5) Technical equipment.

The form and nature of the technical equepment for X-ray testing has been decisively influenced by its being applied to large bridge or roof girders in the workshops, and still more by its application on the actual site of the job.

The characteristics required in modern X-ray apparatus for workshop use are: (a) safety from contact with high-tension conductors; (b) protection from the rays; (c) mobility of the X-ray tube container; and (d) portability of the constituent parts.

These requirements have finally been satisfied by the following measures, on which broad agreement has been reached between different manufacturers:

(a) All high-tension conductors are surrounded by earthed metal conductors.

(b) The only acceptable type of X-ray tube is that known as "protected ray" from which only a relatively narrow bundle of rays can be emitted (compare Fig. 3), the other rays which proceed in all directions from the radiating surface being screened by thick metal walls.

(c) Between the high tension generator and the X-ray tube there is interposed a high tension cable about 10 m in length, allowing the tube to be moved about and brought into its desired position independently, to a considerable degree, of the rest of the apparatus.

(d) To render the plant portable, high tension generators have been available since as early as 1932 in two symmetrical halves so that no constituent unit of a 200-KW plant exceeds 90 kg in weight. Sometimes, with a view to further reduction in weight, the necessary condensers are included within the high tension cable itself (Siemens & Halske A.G.).

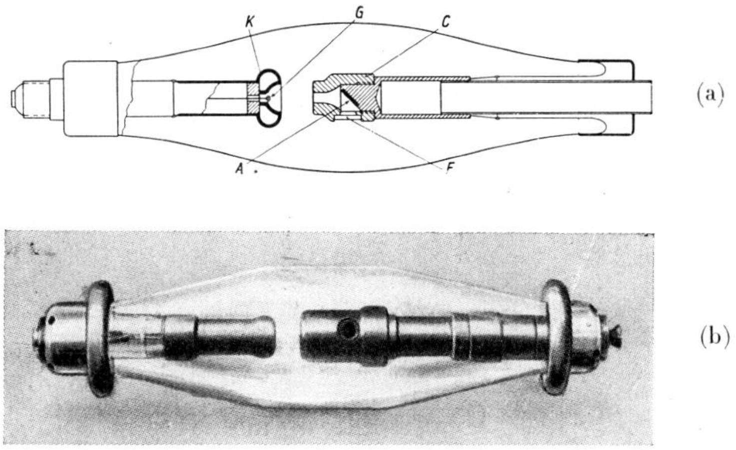


Fig. 3.

Section (a) and View (b) of X-ray lamp for 200 kW oil tension.

A) Wolfram anode plate.
F) Beryllium aperture for exit of rays.
C) Copper-wolfram block.
G) Filament.
K) Cathode.

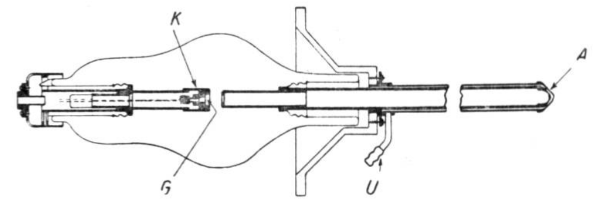
The practicability of X-ray installations built on these lines, in Germany, for use in workshops and on the site, is now attested by some three years of operating experience[2].

Furthermore, the construction of the X-ray tubes has been influenced to an especially notable extent by practical requirements. Relatively short tubes for 200 and 250-KW were made to operate under oil in order to reduce the lenght of insulation and thereby to save weight (Fig. 3). Tubes of this type, however, did not always enable an economical examination to be made — especially in

[2] The following are manufacturers of technical X-ray apparatus in Germany: C. H. F. Müller A.G., Hamburg, Koch & Sterzel A.G., Dresden, R. Seifert & Co., Hamburg, Siemens & Halske A.G., Berlin.

the case of circular welds on pipes and containers — and a new form of hollow-anode X-ray tube has recently been developed (by Siemens & Halske A.G.), in which the electrons reach the cone-shaped anode through a narrow channel held together by a collecting coil; they then undergo retardation within the tube, giving rise to X-rays which are thrown out in all directions through the walls of the tube. This offers further convenient possibilities for the examination of welds (Fig. 4).

The use of X-rays on the site of works also involved a need for new types of film boxes and containers. Following upon a suggestion made by the "Rönt-



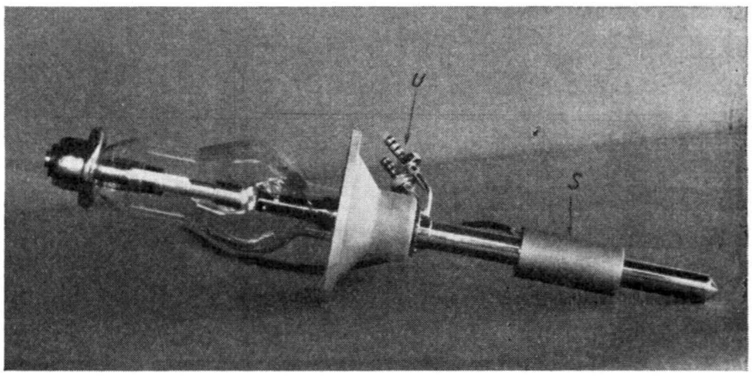


Fig. 4.

Section and View of hollow-anode lamp for testing materials.

A) Platined copper anode.
G) Filament.
K) Cathode
S) Collecting coil.
U) Circulatory cooling.

genstelle" (Central X-Ray Office), rubber film boxes which admit of evacuation are now used in the testing of welds. These consist of rubber bags from which the air is withdrawn by a vacuum pump after inserting the intensifying sheet and film and sealing them up: in this way the external air pressure is made to hold the intensifying sheet uniformly against the film, while the box remains pliable in any direction.

These light boxes are attached to the place of exposure by means of permanent magnets made from an iron-aluminium alloy.

6) Reading & interpretation of X-ray films.

Experience shows that X-ray films are more difficult to read than to produce. So complex are the influences exerted on the X-ray picture by the type and movement of the electrodes, the bevelling of the plates, and the direction of the rays, that frequently the significance of the picture can be ascertained only by comparing a number of exposures made on one and the same structure, assisted if possible by ordinary photographs of ground sections. Fig. 5, 6, 7 & 8 show some typical examples of practical experiments carried out by the "Röntgenstelle" on bridges and building frames. A collection of typical flaws

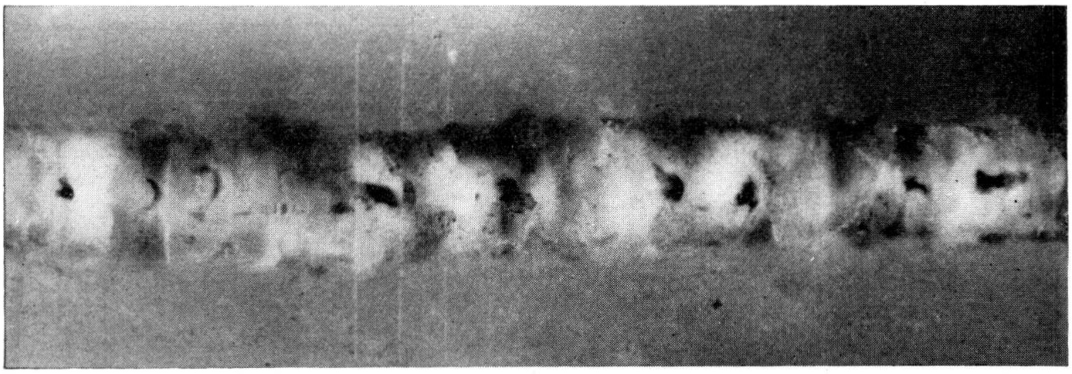


Fig. 5.
Electrically welded X-shaped seam (vertical welding) with coarse slag.

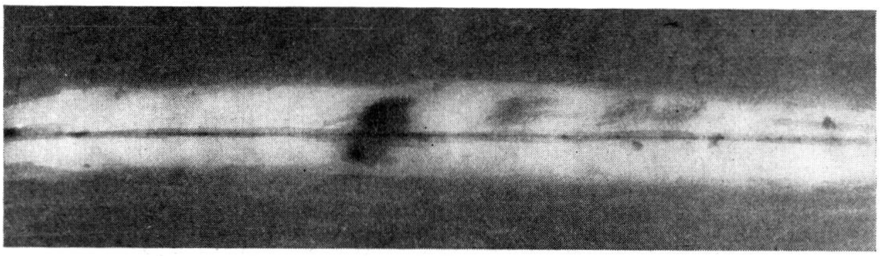


Fig. 6.
Electrically welded X-shaped seam (in web of welded steel superstructure) with not fully welded root.

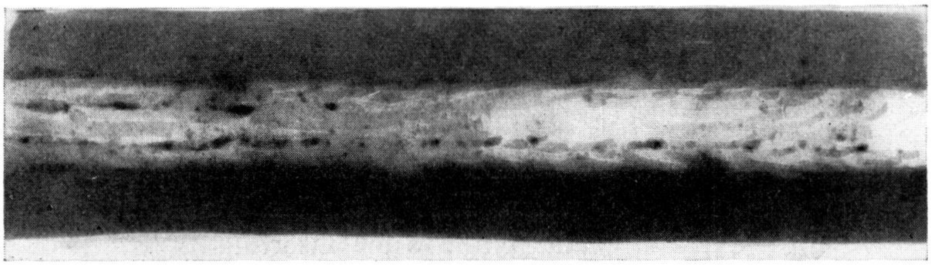


Fig. 7.
Electrically welded X-shaped seam (in web of welded steel superstructure) showing slag lines.

occurring in V, X-shaped and fillet welds has appeared in the journal "Der Stahlbau" (7).

What is most difficult of all, however, is to interpret the faults discovered by means of X-rays from the point of view of their effect on the mechanical properties of the welded connection. Investigations of this relationship have been undertaken in various quarters (8, 9) and Fig. 9 gives some typical examples

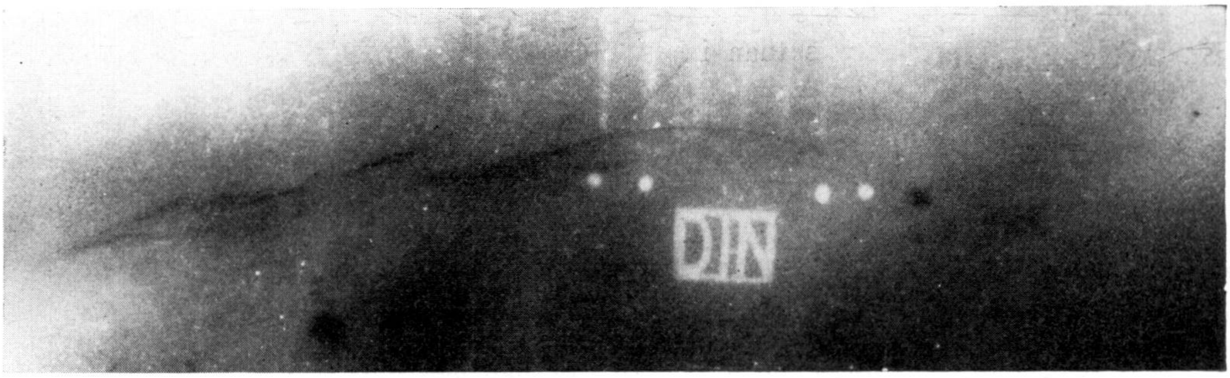


Fig. 8.

Electrically welded fillet seam (end plate joint) showing crack caused by thermal stresses.

of those made at the Röntgenstelle. The upshot of these researches, and of all others hitherto made, is as follows:

The fatigue resistance of welded connections is impaired to a notable extent by imperfect binding, cracks, slag inclusions and bad defects at the root of the weld. On the other hand, provided they do not form a continuous bead-chain, little or no influence is exerted by the presence of small or medium sized pores distributed haphazard.

Fig. 9.

X-ray photos of various types of weld joints, illustrating fatigue strength.

7) Scope of X-ray testing.

In accordance with a regulation of the German State Railways *(Reichsbahn)* dated 27[th] January 1936, the testing of weld seams by X-rays is required in all butt joints of the first category, and (recently) in some of the "neck seams" (joint between flange plate and web) of rolled joists and some of the fillet welds of cross stiffeners. At present some 300 m length of welds are being X-rayed every day in Germany as a result of this regulation.

In the case of structural steelwork there is no regulation as to X-ray testing, and here, for the most part, only purely statical stresses arise. Nevertheless in important industrial work such as welded roof frames, sub-structures for pressure containers, etc., X-ray examinations of the welds are now being carried out.

In structural steelwork subject to static loading the scrutiny of defects is of course much less rigorous than in the case of railway bridges, which have to stand alternating stresses.

8) Organisation of X-ray testing in Germany.

The experiments, described in Section 6), made for the purpose of correlating X-ray results with the mechanical properties of a weld, fall far short of producing a universal key to the endless variety of cases that call for interpretation — a variety which extends not only to the orientation, position, size and shape of the defects, but also to the nature of the materials and of the electrodes and to the nature, magnitude and direction of the stress. To produce so great a diversity of faults intentionally, with a view to their systematic comparison, is a practical impossibility. It is, therefore, impossible at present to lay down any directions for the interpretation of X-ray photographs such that rigid adherence to them will exclude all possibility of error.

This is the difficulty — but also the attraction — of non-destructive methods, which can yield only indirect indications regarding the effects associated with the faults they have been the means of ascertaining. Indeed, the final elimination of such faults calls for intuition grounded on experience — a process similar to medical diagnosis, for which neither textbooks nor collections of photographs are an effective substitute. This circumstance may not be liked by the engineer accustomed to calculation and unwilling to be reminded of the fact that all his precision rests on *assumptions* as to properties of materials, distribution and magnitude of stresses, whose foundation is no better.

In these circumstances the problem of making the X-ray process generally available without prejudice to technical development has been approached, in Germany, on original lines. With the concurrence of the General Inspector of the German road system and that of the supreme authority of the railways, nearly all X-ray photographs taken on welded steel bridges are submitted to the Röntgenstelle after preliminary examination by the appropriate executive officers. The interpretation put forward by the latter is checked by the Röntgenstelle whose conclusion they, in turn, receive back. The purview of the Röntgenstelle extends to the quality of the exposures, to their interpretations as put forward by the officers concerned, and, if necessary, to the causes of the welding defects and the possibility of remedying these. In this way there is a guarantee that all welds on steel bridges throughout Germany shall be scrutinised on uniform lines, and further that all the executives shall be trained to follow the same lines as the "Röntgenstelle". Moreover, such defects can be recognised rapidly if it happens that similar ones have already been encountered and overcome in another structure. Finally, it is found that the continuous supervision of the welders so obtained has an educative effect.

Work in the shops and on the site must not, of course, be exposed to any notable delay. In straightforward cases, therefore, decisions as to whether welds may be accepted or must be improved are reached by the field executives or by delegates from the "Röntgenstelle" on the spot right away. It is only in cases of doubt that a decision has to be obtained from the "Röntgenstelle" itself, which then also calls in a statical expert from the Government Materials Testing Station at Berlin-Dahlem.

The "Röntgenstelle" is equipped for this task with several mobile X-ray laboratories stationed at different points in the Reich. An extensive stock of experience gathered from all these places is thus being capitalised for the interpretation of X-ray films.

Fig. 10 shows one of the mobile X-ray sets and its application at the site.

One indication of the results achieved through this organisation is the fact that the rate of occurrence of queries regarding welded connections was reduced, within three months, to a tenth of its original magnitude.

Fig. 10.
X-ray examination of a welded steel superstructure.

C) Magnetic testing of welded connections.

The processes of non-destructive testing which make use of the disturbances arising in magnetic fields in the presence of flaws, and of the detection of these either by means of vibrating coils or by means of magnetic powder, have not yet been developed to a sufficiently wide scale to allow of critical discussion. It appears likely that the "magnetic tuning method" (the I. G. weld tester produced by the A. E. G.) will be applicable to oxy-acetylene welded connections up to a maximum thickness of 20 mm. The magnetic powder method is also likely to come into use for such welds on thin sheets, but these occur more frequently in the construction of aircraft than in that of bridges and structural work; whether the magnetic powder method will also achieve some significance in the latter should become apparent before long.

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Summary.

The general introduction of fatigue strength tests into the technical-mechanical testing methods of welding showed the great effects of notches and the consequent influence of flaws which show up but little under purely static stressing. To guarantee the quality of welded construction it became necessary to develop such testing methods as do not lead to destruction if flows were to be properly detected. For this purpose the X-ray testing method has proved most successful, since it is physically and technically a fully developed method, which makes it possible in practically all cases to arrive at proper results without incurring excessive costs. Today the technical development of apparatus and auxiliary equipment permits the application of the X-ray methods at site as well as in workshop. The procedure to be adopted for X-ray tests is controlled in Germany by governmental directions which aim at a uniform quality of the photographs obtained by all those applying X-ray testing methods, thus establishing a perfect basis for judging the results.

All testing methods which do not lead to destruction have a common drawback in that they do not permit the final effect of detected flows to be judged. In other words they do not give clear indications as to whether an imperfect weld has to be passed or rejected. To be able to arrive at a more or less sound judgment long experience is required, and this can only be obtained by examination in a central office. In Germany the majority of all X-ray film examinations of welds is therefore carried out by the X-ray Department of the Test House at Berlin-Dahlem.