RADIOGRAPHIC INSPECTION OF WELDS

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ABSTRACT

This paper addresses the difficult problem of evaluating weld integrity of partial penetration type weld joints. Radiographic standards for partial penetration welds have in the past not been considered feasible due to confusing indications on the radiograph, resulting from the partially welded joint. The Army has developed a technique to offset this problem with suitable radiographic standards for conventional weld defects. This technique will be discussed.

INTRODUCTION

To adequately discuss the inspection of welds, it would be valuable to briefly cover the welding process. After this, since we are to consider the radiographic inspection technique, it will be desirable to cover the basic aspects of radiography. Finally, the adaptation of the radiographic procedure to weld inspection will be made.

Welding as applied to all materials would be a much too broad a category for this discussion. To make the subject manageable; only metals will be considered, specifically aluminum and steel.

Weld Bead Material Characteristics

The weld bead is a cast type metal, which is an alloy of the base metal being welded and that of the welding rod or wire added. During the welding process, this alloy is subjected to a very severe thermal environment which affects its metallurgical properties such as ductility, tensile strength, grain size and uniformity, impact qualities and alloy purity. Elements in steel such as sulphur, phosphorous, hydrogen have undesirable effects and every effort is made to eliminate them during the making of the metal and during welding. Base metal used for weldments is limited for practical reasons to compositions that can be readily fabricated without appreciable defects. One major stipulation restricts carbon hardening elements for steel to certain maximum levels. Too often the base material is selected from handbooks without recourse to materials or production engineering assistance. Many times troubles encountered in producing sound, crack free welds is traceable to difficult to weld base material. Filler material required for a weld is basically determined by the welding process. For some welds, no filler metal is required, in which case the weld metal consists of melted base metal. In addition to the restrictions imposed by the welding process, the choice of filler metal is based on mechanical and metallurgical considerations. The first consideration being that the filler metal have sufficient strength and ductility to perform adequately under the stress system imposed. Weld metal is a cast dendritic structure of comparatively low ductility and therefore, it is usually the practice to obtain a weld deposit of equal or greater strength than the base metal. Then in case of overstressing, the deformation will occur in the base metal which can better withstand deformation. This practice may not be desirable since other material properties other than strength and ductility may be needed, such as toughness, strain aging, creep, corrosion or wear resistance.

Weld Fabrication

The temperature in a weld joint will range from above the melting point to ambient of the section being welded. These temperatures cause expansion and contraction, chemical reactions and extreme mechanical stress in a weldment. The thermal gradient from ambient base material temperature to melting and the associated cooling rates represent a range of heat treating cycles of both good and extremely poor practices, resulting in questionable weld integrity. The molten weld metal may react with constituents of the surrounding atmosphere such as oxygen, hydrogen, nitrogen or gaseous compounds of these elements with carbon, causing degradation of the weld joint. Contamination by gases can be avoided by proper manipulation and utilization of the atmospheric shielding provided for a particular weld process. Most gases evolve from the molten weld metal readily, but time must be allowed for the gases to escape before the weld melt solidifies and entraps them. During the welding process, the operator must manipulate the heat source for two effects, (1) to produce a molten puddle of base material to fuse with the filler metal and (2) to exert control over the rate of solidification.

From this cursory look at the welding process, we see that many of the inherent problems confronted in obtaining a sound casting are also present during the weld process, i.e., material porosity, gas cavities slag inclusions, tears, etc. There are other defects inherent to welding alone, i.e., lack of fusion, incomplete joint penetration, cracking, overlap, weld crater, etc. Most of these defects can be located with good radiographic techniques.

Radiographic Process

X-rays are a form of radiant energy similar to visible light. They are of extremely short wave length and it is this characteristic that provides for their ability to penetrate materials which stop ordinary light. X-rays have all of the properties of visible light besides some which are characteristic to themselves, i.e., visible light is refracted by glass and therefore is capable of being focused by a lens made from it, however, for all practical purposes x-rays are not refracted and cannot be focused by a glass lens (their refraction by glass is ever so slight). Since radiography involves exposures made with Gamma radiation as well as x-rays, it is expedient to state that Gamma rays, although similar to x-rays, usually have a shorter wave length and are more...
penetrating. They are distinguished from x-rays by their source and not their nature. Gamma rays are emitted from disintegrating nuclei of radioactive substances, whereas x-rays are produced when electrons, traveling at high speed, collide with matter in the tube of a conventional static x-ray machine. An incandescent filament supplies the electrons and forms the cathode (negative electrode). The tube target is made the anode (positive electrode). A high voltage potential is applied across the cathode and anode, providing an accelerating force to the electrons produced by the filament. The sudden stopping of these fast moving electrons near the surface of the target anode results in the generation of x-rays. The higher the temperature of the filament, the greater its emission of electrons and the larger the resulting tube current. Other conditions remaining the same, the x-ray output is proportional to the tube current. Most of the energy applied to the tube is transformed into heat at the focal spot (positive electrode), with only a small portion being transformed into x-rays. The focal spot should be as small as feasible so as to obtain the sharpest possible definition (sharpness of image). However, the smaller the focal spot the less energy it will stand without damage. The higher the voltage the greater the speed of the electrons striking the target (increasing focal spot deterioration) with an associated decrease in wave length and a consequent increase in penetrating power (x-ray intensity). It is to be noted that x-rays produced at high kilovolts contain all of the wave lengths of x-rays that would be produced at a lower kilovoltage plus additional shorter wave lengths having greater penetrating capability. Practical thickness limitations for typical x-ray machines are shown in the attached table. The intensity of gamma radiation (disintegrating nuclei of radioactive substance) is proportional to the source strength in curies, often referred to as "specific activity," expressed in terms of "curies per gram" or "curies per cubic centimeter."

Making A Radiograph - A radiograph is a photographic record produced by passing penetrating radiation through a specimen onto a sensitized film, thus producing a shadow graph of the specimen. Penetrating radiation causes an invisible change to the coating on the film. The exposed areas become dark when the film is immersed in a developing solution; the degree of darkening dependent upon the extent of the exposure. After adequate development, the film is rinsed which stops development. Next the film is placed in a fixing bath to remove the fixer. The basic features of a radiographic exposure are shown in Figure 2. The diagram shows the focal spot as a small area in the x-ray tube from which the radiation is emitted. The radiation travels in straight lines to the specimen. Upon entering the specimen, some rays pass through while others are absorbed. The amount which is transmitted depends upon both the nature of the material and its thickness. If the specimen contains a void, radiation passing through will be less impeded and more energy will be transmitted through the surrounding material. This will result in a dark spot on the development film corresponding to the projected position of the void, thus a shadow picture is formed of the specimen. The direct action of x-rays on a sensitized film can often be enhanced by the use of intensifying screens, which are placed on each side of the film. These are generally of two types, (1) calcium tungstate, which converts x-rays into visible light which aids in the film exposure and (2) lead foil, which when penetrated by radiation gives off free electrons which also benefit the exposure of the radiographic film. Lead foil has still another benefiting action of filtering out scattered radiation which improves the contrast, detail and clarity of a radiograph image. There are several types of radiographic film available, each of which has a special purpose to enhance radiographic results for a particular application, Fig. 3.

Radiographic Inspection - The inspection process is utilized to determine that the work being performed complies with the prescribed job or product requirements. Although there are several ways to inspect or evaluate welds, we will consider only the radiographic technique. It should be remembered however, that radiography may not necessarily be the best choice for all weld inspections and may often need to be verified by other types of tests, i.e., ultrasonics, physical tests. When considering any test there are some fundamental aspects which should be established, i.e., the object of the test, selection of the specimen, cost factor, validity of the test and the usefulness or value of the results. These test fundamentals need to be combined with common sense for satisfactory inspection. (1)

Radiography has some inherent limitations which must be considered to obtain satisfactory results. Since a radiograph is a shadow picture of an object placed in the path of an x-ray beam, the forming of an image is influenced by the relative positions of the object and the film, the direction of the beam and the size of the source. For these reasons, familiarity with shadow formations is important for making and interpreting radiographs to assure radiographic image sharpness and minimum distortion. Figure 4 shows the effects of changing the size of the source and of changing the relative positions of source, object and card (film). It can be concluded then that the following conditions are needed to produce sharp, true shadowgraphs: (2)

a. The source of x-rays should be as far from the object as practicable.

b. The source of x-rays should be small as possible.

c. The recording surface (film) should be as close to the object as possible.

d. The x-rays should be directed perpendicular to the recording surface.

e. The plane of the object and the plane of the recording surface should be parallel.

The enlargement of the object shadow will occur if the object is not in close contact with the film and the degree of enlargement being dependent upon the relative distance of the object from the film and from the x-ray source.

Radiographic Sensitivity - Two factors affecting radiographic visibility are Radiographic contrast and definition. Radiographic contrast is the difference in film densities for various areas of a radiograph. It depends upon both subject contrast and film contrast. Subject contrast is the relation
of x-ray intensities transmitted by various portions of a specimen. Subject contrast depends upon the characteristics of the specimen, the radiation used and the effects of scattered radiation. Film contrast depends upon the type of film, its processing and density (darkness). Definition is the sharpness of the image outline. It is dependent upon the radiation quality, geometry of radiographic setup and type of film and screens used. A check on the adequacy of a radiograph is made by use of a penetrameter, which is placed on the source side of a specimen. It has a thickness of a definite proportion of the specimen thickness, i.e., 2 percent, 1 percent, 5 percent. If the outline of the penetrameter shows clearly in the radiograph, the technique is considered satisfactory. Penetrameters may contain slots or holes of various sizes and judgment is based upon radiographic display of these holes. It should be pointed out that even if a hole in a penetrameter is visible on a radiograph, a void of the same diameter and thickness may not be visible. The penetrameter holes have sharp edges which give abrupt changes in metal thickness where a natural cavity has a more rounded edge which gives a gradual change. The image of the penetrameter hole will be sharper and more easily seen in a radiograph than will a natural cavity. Also, a fine crack may be quite extensive, however, if the x-rays pass across the thickness of the crack it probably will not be visible. Consequently, a penetrameter is used to check radiographic technique and not as a measure of the size of void which can be shown.

Typical Weld Joint Flaws - In order to utilize any inspection process, realistic standards of acceptability must be established. These standards will depend upon many aspects of the welded component, i.e., its application to the base material, cost, etc. Since the perfect weld has never existed and only degrees of weld imperfection will be obtainable, the following examples of weld joint discontinuities are presented:

Figures 5 and 6 show the recommended radiographic procedures for partial penetration weld joint designs. Partial penetration welds differ from full penetration welds and require more care when being radiographed to assure complete or maximum weld coverage with minimum interference from the normal unfused weld joint land.

Figures 7 and 8 illustrate radiation angles for two typical weld joint designs.

Figure 9 - Gas cavities in aluminum weld.

Figures 10 and 11 - Incomplete penetration in aluminum and steel welds respectively.

Figures 12 and 13 - Lack of fusion in aluminum and steel welds respectively.

Figure 14 - Ungraded conditions in aluminum welds.

Figure 15 - Fine scattered porosity in steel welds.

Figure 16 - Course scattered porosity in steel welds.

CONCLUSION

Radiographic inspection of welds is a valuable tool which must be utilized with caution, taking into account all of the known technique, hazards and limitations so as not to be fooled by the apparent simplicity of radiography. It is often possible to have a good defect-free radiograph and an associated defective component.

REFERENCES

1. Course Handout and notes from "Special Course in Welding Inspection", U. S. Army Ordnance Corps - Watertown Arsenal, Watertown, 72, Mass.
Figure 1. Schematic diagram of an X-ray Tube

Figure 2. X-Ray Tube Schematic

Figure 3. Typical X-ray Machines and Their Applications

<table>
<thead>
<tr>
<th>Maximum Voltage (kV)</th>
<th>Screens</th>
<th>Applications and Approximate Practical Thickness Limits</th>
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<tbody>
<tr>
<td>50</td>
<td>Phone</td>
<td>X-rays of thin metallic sections, wood, plastics, biological specimens, etc.</td>
</tr>
<tr>
<td>150</td>
<td>Lead or lead foil</td>
<td>Light alloys, 0.25-inch aluminum or equivalent, 1-inch steel, or equivalent.</td>
</tr>
<tr>
<td>250</td>
<td>Lead foil</td>
<td>1-inch steel, or equivalent.</td>
</tr>
<tr>
<td>400</td>
<td>Lead foil</td>
<td>1-inch steel, or equivalent.</td>
</tr>
<tr>
<td>1000</td>
<td>Lead foil</td>
<td>4-inch steel, or equivalent.</td>
</tr>
<tr>
<td>2000</td>
<td>Lead foil</td>
<td>8-inch steel, or equivalent.</td>
</tr>
<tr>
<td>15-24 Mev</td>
<td>Lead foil</td>
<td>16-inch steel, or equivalent.</td>
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Figure 4. General Geometric Principles of Shadow Formation
Figure 5. Recommended Radiographic Procedures for Partial Penetration Joint Designs

Figure 6. Recommended Radiographic Procedures for Partial Penetration Joint Designs

Figure 7. Correct and Incorrect Radiographic Procedure for Joint Design (C)

Figure 8. Correct and Incorrect Radiographic Procedure for Joint Design (A)
Figure 9. Reference Standards for Gas Cavities - Aluminum Welds

Figure 10. Examples of Incomplete Penetration Correlated with Weld Cross Sections - Aluminum Welds

Figure 11. Varying Degrees of Incomplete Penetration in Steel Welds, Correlated with Weld Cross Sections

Figure 12. Examples of Lack of Fusion Correlated with Weld Cross Sections - Aluminum Welds
Figure 13. Lack of Fusion in Steel Welds, Correlated with Weld Cross Sections

Figure 14. Examples of Ungraded Conditions Correlated with Weld Cross Sections - Aluminum Welds

Figure 15. Reference Standards for Fuzzy Scattered Porosity in Steel Welds

Figure 16. Reference Standards for Coarse Scattered Porosity in Steel Welds
Figure 17. Reference Standards for Linear Porosity in Steel Welds

Figure 18. Reference Standards for Clustered Porosity in Steel Welds

Figure 19. Reference Standards for Scattered Slag Inclusions in Steel Welds