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AEROSPACE RECOMMENDED PRACTICE

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Nondestructive Testing of Electron Beam Welded Joints in Titanium-Base Alloys

RATIONALE

ARP1333 is currently not being used in industry.

CANCELLATION NOTICE

This document has been declared "CANCELLED" as of January 2007. By this action, this document will remain listed in the Numerical Section of the Aerospace Standards Index.

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1. SCOPE: This Aerospace Recommended Practice (ARP) describes techniques for nondestructive test (NDT) evaluation of the quality of electron beam (EB) welded joints in titanium-base alloys with depths of section at the weld up to 2 in. (51 mm).

2. GENERAL:

2.1 The complexity and importance of valid nondestructive inspection of structurally critical EB welds are such that the design engineer must give careful attention to the capabilities and limitations of the several NDT procedures during all phases of the design effort.

2.2 Design of the welded joint must include consideration of not only the EB welding process but also the need to prepare the weld for NDT by machining and the potential need for rewelding in case the weld fails initially to pass specified acceptance criteria.

2.3 Flaws in EB welds of titanium-base alloys are of four basic types:

(1) Bursts: This type of defect is a disc-shaped flaw on the weld centerline. The length and depth usually range between ten and twenty times its width.

(2) Voids: These are irregularly shaped flaws whose depth dimension exceeds their length and whose width can encompass the entire width of the fusion zone of the EB weld.

(3) Porosity: This consists of round (or oval, within 2:1) shaped voids, typical of the porosity found in all welding processes. The voids may be isolated, linear, or stacked in the weld-depth dimension.

(4) Lack of Fusion: This is a defect in which a portion of the weld joint is not fused or melted together.

3. NDT PROCEDURES: Five separate inspection procedures are recommended for the complete NDT evaluation of an electron beam weld in titanium-base alloys. These are:

(1) Visual examination
(2) Witness line examination
(3) Radiographic examination
(4) Ultrasonic inspection
(5) Fluorescent penetrant inspection

3.1 Visual Examination: This procedure uses a modified depth gauge with a dial indicator to determine the depth of "underfill" or "undercut" existing on the face- or gun-side of the weld and to determine the depth of "suckback" existing on the root- or beam-exit-side of the weld. Fig. 1 illustrates such measurement.

3.1.1 This measurement is made to verify that the depths of face-side underfill or root-side suckback do not exceed the postweld machining allowances which are provided by the weld joint design to assure the smooth machined surface needed for subsequent NDT inspection procedures. However, visual examination and measurements are usable only if the pre-weld joint mismatch and postweld machining allowance are known. Typical examples of information sought in visual examination are shown in Figs. 2, 3, and 4.

NOTE. The postweld machining allowance will normally be specified with a tolerance, e.g., 0.090 in. ± 0.010 (2.28 mm ± 0.25). When making the indicated measurements to assure clean-up of any underfill, only the minimum allowance is considered, e.g., 0.080 in. (2.03 mm) for the example given here.

3.2 Witness Line Examination:

3.2.1 The aspect ratio of the weld (i.e., the ratio of weld depth to weld width) although significant from a welding design viewpoint, presents a challenge during postweld inspection to obtain evidence that fusion has taken place along the complete length and depth of the weld.

3.2.1.1 Incomplete fusion caused by lack of penetration is readily detected from the absence of a bead on the root side. The less apparent but more dangerous lack of fusion occurring within the depth of the weld can best be evaluated by the use of witness lines.

3.2.1.2 Witness lines are equally spaced lines scribed adjacent and parallel to the weld joint on both the face and root sides of the joint prior to welding.

3.2.1.3 For joints 0.5 - 2.0 in. (13 - 51 mm) deep and with bead width of 0.060 - 0.100 in. (1.52 - 2.54 mm), it is recommended that the witness line spacing be 0.030 in. (0.76 mm). (For metric dimensions a line spacing of 1.00 mm may be more practical.)

3.2.1.4 Measurement is accomplished at the completion of the production weld by recording the number of witness line spaces remaining visible.

3.2.1.5 For most EB welds the weld bead configuration on the face is wider than that on the root side. This necessitatesd the examination of witness lines on both sides to determine the center-line of the weld in relation to the original joint line.

3.2.1.6 The thickness of the joint being welded, in combination with the welding parameters which are controlled to provide a satisfactory weld, does not always produce a symmetrical fusion zone, i.e., a straight-sided weld. Often, the width of the weld bead on the face of the weld is much greater than the bead on the root side of the weld. Neither of these, however, provides a true indication of the width of the actual fusion zone (See Fig. 5). The visible beads do permit a reasonably close estimate of the weld center line location. The actual minimum fusion zone width is determined by cross-section metallographic examination of preproduction test welds made prior to production welding. The welding parameters such as gun-to-work distance, direction of gun travel (e.g., horizontal, or vertically down), voltage, current, speed, and focal current which are used on the preproduction test weld must be the same as those to be used for the production welds:

3.2.2 Face Side Examination:

3.2.2.1 Typical requirement: The joint to be welded shall fall within the central one-third of the visible melted metal. Two examples are given in Figs. 6 and 7.

3.2.2.2 If rewelding is indicated because of a rejection based on witness line examination, the presence of the witness lines and knowledge of the direction of excessive displacement of the weld center-line can be used as an indexing aid to align properly the EB gun and workpiece for rewelding.

3.2.3 Root Side Examination:

3.2.3.1 Typical requirement: Witness line examination shall demonstrate that the center-line of the weld is not displaced from the original joint line of the weld to the extent that a minimum fusion zone width of 0.010 in. (0.25 mm) is not assured.

3.2.3.2 Postweld witness line examination of the root side bead and corresponding analysis require that measurement be made of the minimum fusion zone width that can be expected in production welds made with the same specified set of welding parameters used for the test samples. Two examples are given in Figs. 8 and 9. Acceptance charts as illustrated in Fig. 10 are helpful when a substantial number of like welds are to be evaluated.

3.3 Radiographic Examination: Radiographic inspection should be used as a basic method for nondestructive testing of EB welds in titanium-base alloys, as it is with other fusion welding techniques. The nature of the EB welding process, especially with respect to techniques used to repair flaws and the procedures for locating the flaws, imposes additional burdens upon the X-ray technician, as compared with the techniques used with more conventional fusion welding processes. The importance of defect location is covered in detail in 3.3.2. The orientation of flaws is greatly influenced by the depth-to-width ratio of the weld.

3.3.1 Flaw Detection:

3.3.1.1 Detection of an unfused portion of a joint is extremely difficult using ordinary X-ray techniques because of the shrinkage occurring during solidification of the molten weld metal which results in an extremely tight, almost crack-like, flaw remaining.

3.3.1.2 As with radiographic detection of any crack, the angle of incidence of the X-ray to the plane of the flaw is extremely critical.

3.3.1.3 It is recommended that EB welds be examined at a 1% sensitivity level as shown by the use of appropriate penetrameters. This sensitivity is achieved through judicious selection of exposure parameters and exposure times coupled with use of a truly sensitive film.

3.3.1.4 The size and orientation of bursts and voids aid in their ready detection through the use of radiographic inspection.

3.3.1.5 Porosity may or may not be detected, depending upon the size, quantity, and orientation of the pores, and the sensitivity of the X-ray technique being used.

3.3.1.6 Optimum sensitivity in flaw detection is obtained by machining the face and root side of each weld prior to radiographic examination.

3.3.1.7 Radiographic examination and ultrasonic inspection can be mutually complementary in evaluating the size and location of flaws.

3.3.2 Defect Location:

3.3.2.1 The importance of accurate defect location in an EB weld must be considered in light of the repair weld techniques of the EB welding process compared to those of the more conventional welding processes such as GTA welding. In the latter process, when a defect is found that is unacceptable, the normal procedure is to machine out the flaw and a sizable amount of material surrounding the flaw. This area can then be locally rewelded using additional filler wire.

3.3.2.2 The majority of EB weld defects are repaired by making a second EB weld along the initial weld, traversing over the defect. A number of factors must be taken into consideration to ensure a satisfactory repair weld.

3.3.2.2.1 First and of most importance, provisions must be made to assure that the X-ray source is coplanar with the weld centerline. Bubble-levels are useful for aligning the surface of the welded part so it is perpendicular to the X-ray beam.

3.3.2.2.2 Second, the location of the defect must be accurately indicated by punch marks on the machined face of the weld in order that the welding engineer will have a target to aim at during the repair process.

3.3.2.2.3 Third, the accuracy of aligning the EB gun to the punch mark and the capability of the electron beam to strike the center of the punch mark must be taken into account.

3.3.2.2.4 Fourth, the width of the weld to be produced during the repair effort must be considered.

3.3.2.2.5 A brief example, somewhat exaggerated, is diagrammed in Fig. 11 and illustrates the potential hazards involved.

Assumptions:

X-ray source to face of weld	= 36 in. (914 mm)
Thickness of joint	= 1.00 in. (25.4 mm)
Depth of defect	= 0.50 in. (12.7 mm)
Size of defect	= 0.070 in. (1.78 mm) dia
Width of repair weld	= 0.100 in. (2.54 mm)

Errors Assumed:

X-ray source 5 deg (0.087 rad) away from plane of weld center-line Defect-identifying punch mark located 0.015 in. (0.38 mm) off defect EB beam deflection = 0.015 in. (0.38 mm)

The punch mark, if precisely located over the defect in this example, would actually be 0.040 in. (1.02 mm) to the left of the defect. If it is assumed that the technician making the punch mark errs by an additional 0.015 in. (0.38 mm), the target for the repair weld will then be 0.055 in. (1.40 mm) from the plane of the flaw.

The centerline of the repair weld could be off target by an additional 0.015 in. (0.38 mm) due to beam deflection. Thus the centerline of the repair weld misses the center of the defect by 0.070 in. (1.78 mm).

Because the repair weld is only 0.100 in. (2.54 mm) wide, it is unlikely that the flaw would be remelted and repaired.

3.3.2.2.6 This type of error can be overcome through care in aligning the X-ray source to the workpiece being examined, experience on the part of the X-ray technician in locating the defect by use of lead markers prior to punch-marking the defect location, and use of wider-than-normal weld beads in the repair weld.

3.4 <u>Ultrasonic Inspection:</u>

3.4.1 The extreme sensitivity of ultrasonic inspection makes it a valuable tool in the complete NDT of EB welds.

3.4.1.1 The narrowness of the EB weld dictates use of a focal beam transducer. Experience gained during several years of production welding inspection indicates a 15 MHz transducer to be optimum. Where a focal beam transducer is used, inspection of welds whose thickness exceeds 0.50 in. (12.7 mm) must be carried out in increments of 0.50 in. (12.7 mm) by placing the focal zone at selected depths within the weld and electronically gating out responses from all other depths. Thus, a 2.00 in. (50.8 mm) weld would be examined four times, each examination being 0.50 in. (12.7 mm) deeper than the previous one.

3.4.1.2 Prior to examination of production welds, the ultrasonic equipment should be calibrated against a set of 1:64 ultrasonic standard reference blocks. If available, these blocks should be of the same basic metal as that to be examined in production.

3.4.1.2.1 When testing weldments in parts having convex surfaces (with a radius of curvature of 4 in. (102 mm) or less), convex surface standards should be used for instrument calibration and weld evaluation. When testing weldments in parts having concave entry surfaces (with a radius of curvature of 5 in. (127 mm) or less), concave surface standards should be used for instrument calibration and weld evaluation. The configuration of convex and concave standards must be agreed upon by purchaser and vendor.

3.4.1.3 The water immersion technique provides the best sensitivity, enabling an automated system to be used and a permanent record, or C-scan, to be produced. The weld under examination should be inspected with the transducer scanning along the length of the weld and indexing across the weld at 0.010 in. (0.25 mm) increments with each reversal of direction.

3.4.1.4 For critical structures it is recommended that a C-scan of each weld examination be obtained. The alarm level selected for print-out on the C-scan should be set at 10 - 15% of the response obtained from the previously mentioned reference blocks. This rather low alarm level is suggested because most production welds are examined from the face side of the weld rather than in the optimum direction, perpendicular to the plane of the weld centerline.

3.4.1.5 Upon completion of the initial scanning operation, which provides the permanent C-scan, the ultrasonic technician then should manually control the transducer movement to examine those specific areas of the weld shown by the C-scan to contain flaws. The magnitude and depth of internal flaws are determined by observation of the calibrated cathode ray tube, and the information so obtained is noted adjacent to the appropriate print-outs on the C-scan.

3.4.2 Combining the information gathered during ultrasonic examination with additional information obtained during radiographic examination provides valuable knowledge for selection of the repair weld technique to be employed. For example, the radiographic, examination may reveal a flaw whose size is unacceptable. The depth of the flaw as determined by ultrasonic examination is then the basis for selecting a full penetration repair weld or a partial penetration repair weld.

3.4.3 Historically, a major drawback associated with ultrasonic examination has been the inability to accurately dimension the flaws causing the sonic response. It is strongly recommended that destructive metallographic examination be performed on as many as practical of the test welds found to contain flaws either radiographically or sonically. The correlation between actual flaw sizes and NDT results is invaluable to the ultrasonic technician and instills confidence in those who must act upon the information gathered during the NDT examination.

3.5 <u>Fluorescent Penetrant Inspection:</u>

3.5.1 This is the final examination procedure recommended for a complete NDT of EB welds of titanium-base alloys. This procedure is recommended due to the recognized state-of-the-art problem of near-surface resolution using the ultrasonic process and the resolving difficulty in radiography when encountering small surface flaws, especially when the weld being examined is greater than 1.00 in. (25.4 mm) thick.

3.5.2 An acid pickle removing approximately 0.0015 in. (0.038 mm) of material is recommended to enhance the sensitivity of the penetrant inspection. All traces of acid should be removed by a water rinse followed by a warm air dry.

3.5.3 A halogen-free, high-sensitivity grade, post-emulsification or water-washable type of fluorescent penetrant system should be used. Penetrant dwell time should be at least 15 minutes. The temperature of the part during the drying operation should not exceed 170° F (77° C). Non-aqueous spray developers should be used.

3.5.4 Where structural considerations dictate that a stress-relief treatment be applied to the final welded assembly, 100% fluorescent penetrant inspection of all welds should be performed after the stress-relief cycle. If the stress-relief is accomplished in an air furnace, the examination should be preceded by an acid descaling treatment removing 0.0007 - 0.0015 in. (0.018 - 0.038 mm) of material. If stress-relief is performed in a vacuum furnace or inert gas environment, the inspection should be preceded by a flash acid pickling operation. All traces of acid should be removed by a water rinse followed by a warm air dry.

4. ACCEPTANCE PHILOSOPHY:

4.1 For a welded structure, such as a uniformly loaded pressure vessel, a single acceptance criterion is feasible. For a composite structure containing numerous welds of varying thicknesses and stress levels, one weld to another, or even in various portions of the same weld, consideration should be given to zoned drawings for guidance of the procedure. These drawings should establish the NDT acceptance criteria applicable to the noted areas, based upon design characteristics and expected service conditions.

4.2 There is no question that the preproduction design, analysis, and test programs are expensive. However, the initial costs are usually amortized in production by reducing the recycling time to perform unnecessary repair welding brought about by the establishment of overly conservative acceptance criteria.

4.3 Test programs should be planned, based upon fracture mechanics and flaw growth considerations. As with other welding processes, deliberate production of a desired flaw to be used as a test specimen is difficult in EB welding; therefore, the classic precracked fatigue-grown flaw may be used.

4.4 Fatigue testing should be conducted using the anticipated loading spectrum of the structure being welded. Flaw growth data thus generated can then be applied in establishing more realistic flaw acceptance criteria for the various welds contained in a composite structure.

5. WRITTEN PROCEDURES:

5.1 All inspections performed in accordance with this recommended practice should be done to a detailed written procedure for the component to be tested. Procedures should be agreed upon by purchaser and vendor. At least one copy of the procedure should be readily available to applicable inspection personnel for reference and use. The written procedure should comply with the general requirements contained herein and should provide all of the specific information required to set up and perform the test. Each procedure should include at least the following information:

5.1.1 Specific part number and configuration to be tested, stage of fabrication, and surface preparation requirements.

5.1.2 Manufacturer and model number of any instrumentation or material to be used.

5.1.3 Scan plan for ultrasonic test, and exposure plan (film placement and source location) for X-ray.

5.1.4 Method of establishing sensitivity for ultrasonic, and exposure data for X-ray.

5.1.5 Acceptance criteria for each inspection method.

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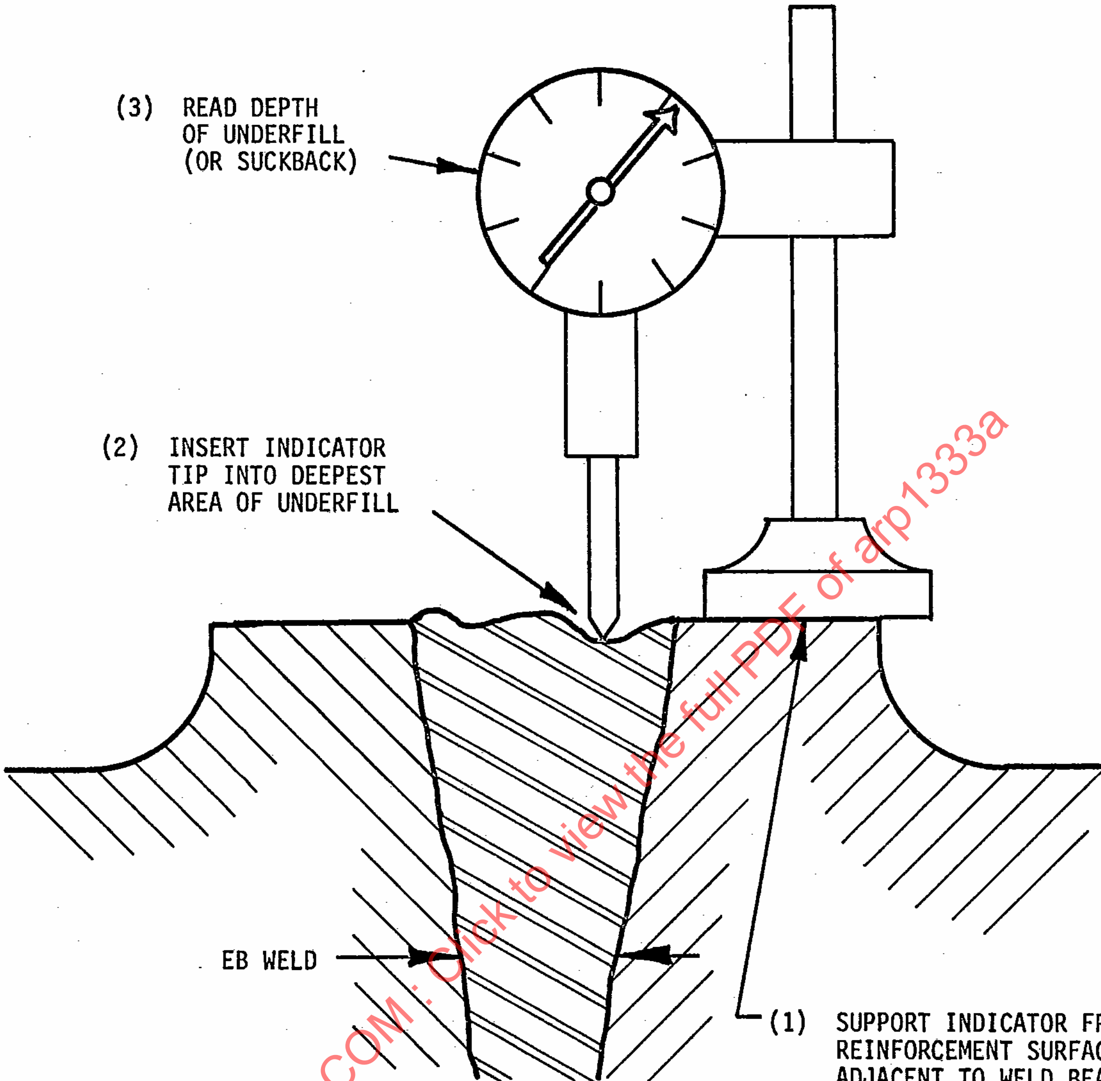
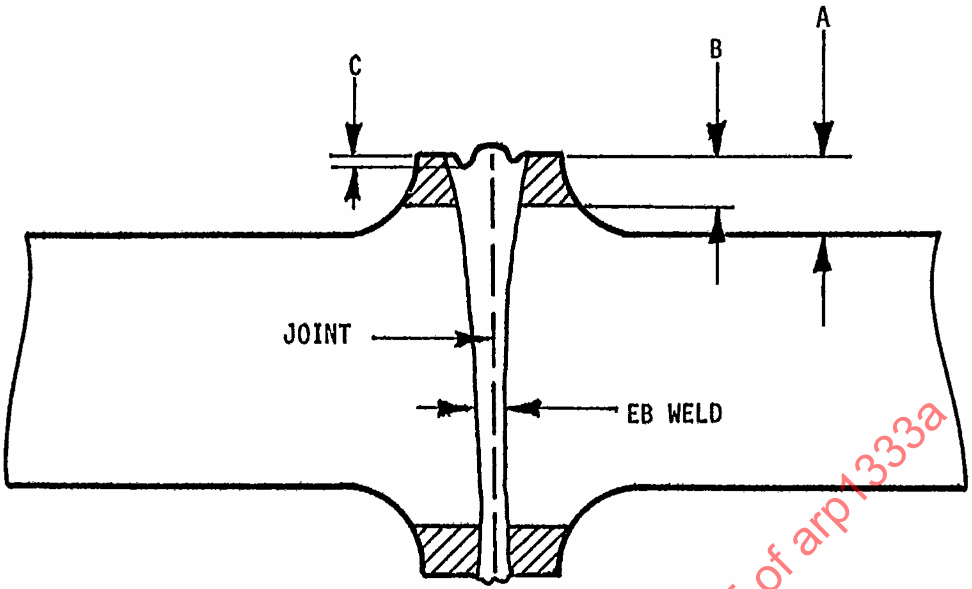
SAE AEROSPACE MATERIALS DIVISION



DIAL INDICATOR MEASUREMENT OF UNDERFILL (OR SUCKBACK)

FIGURE 1



A = JOINT REINFORCEMENT

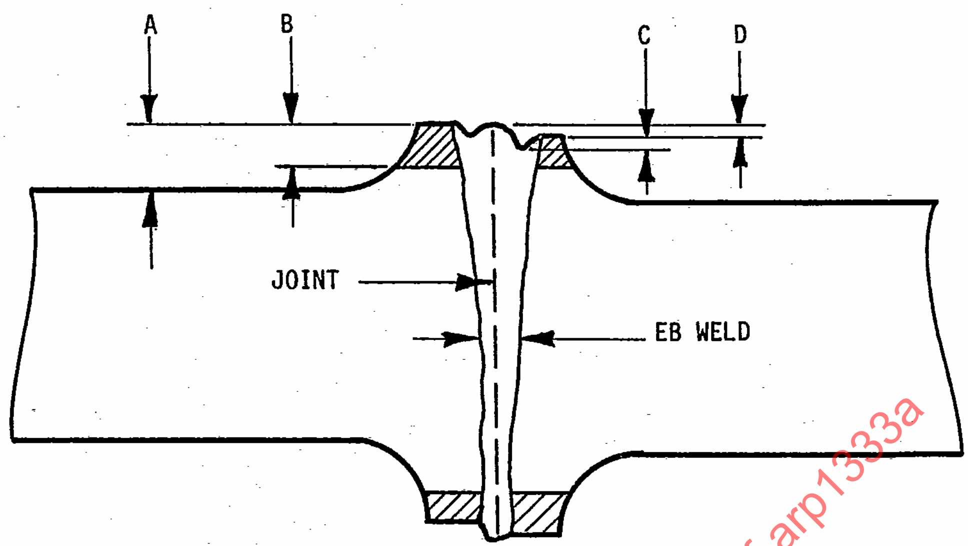
B = POSTWELD MACHINING ALLOWANCE

C = DEPTH OF UNDERFILL (OR SUCKBACK)

C< B IS REQUIRED TO ASSURE A SMOOTH MACHINED SURFACE

JOINT WITH ZERO MISMATCH PRIOR TO WELDING

FIGURE 2



A = JOINT REINFORCEMENT

B = POSTWELD MACHINING ALLOWANCE (MACHINING MUST BE STARTED FROM HIGH SIDE OF JOINT MISMATCH, OTHERWISE, MATERIAL NEEDED FOR POSSIBLE REWELD WILL BE LACKING)

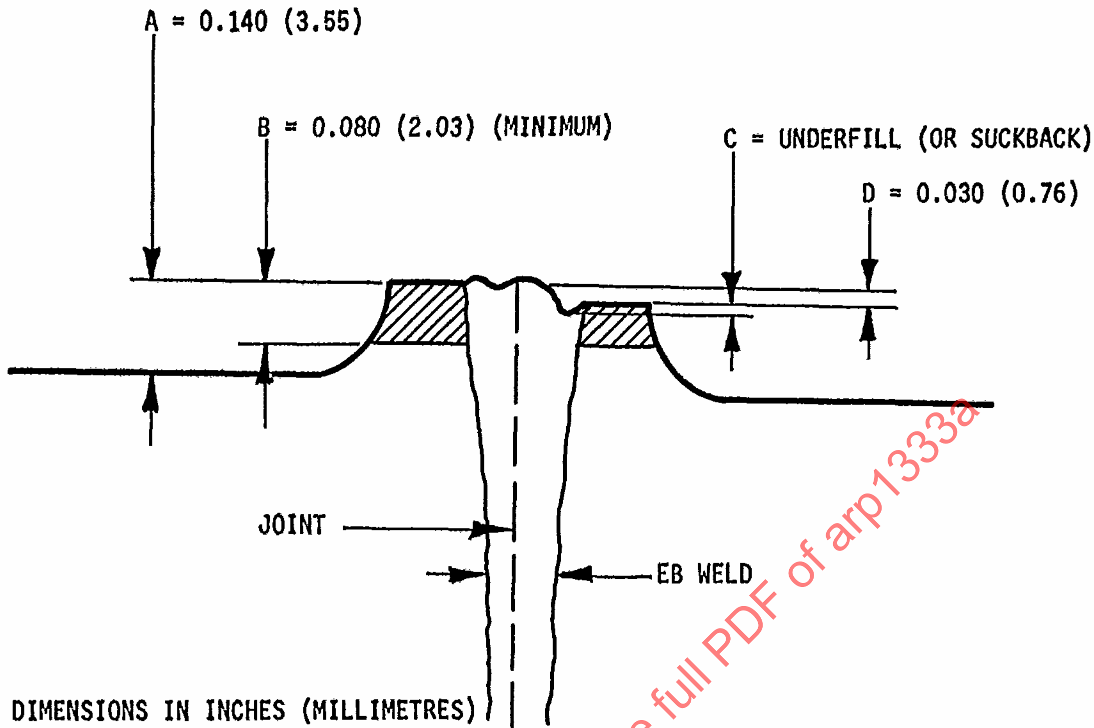
C = DEPTH OF UNDERFILL (OR SUCKBACK) (MUST BE MEASURED FROM LOW SIDE OF JOINT MISMATCH)

D = JOINT MISMATCH

$C < (B - D)$ IS REQUIRED TO ASSURE A SMOOTH MACHINED SURFACE

JOINT WITH MISMATCH PRIOR TO WELDING

FIGURE 3



DIMENSIONS IN INCHES (MILLIMETRES)

A = JOINT REINFORCEMENT

B = POSTWELD MACHINING ALLOWANCE

C = DEPTH OF UNDERFILL (OR SUCKBACK), MEASURED ON LOW SIDE OF JOINT MISMATCH

D = JOINT MISMATCH

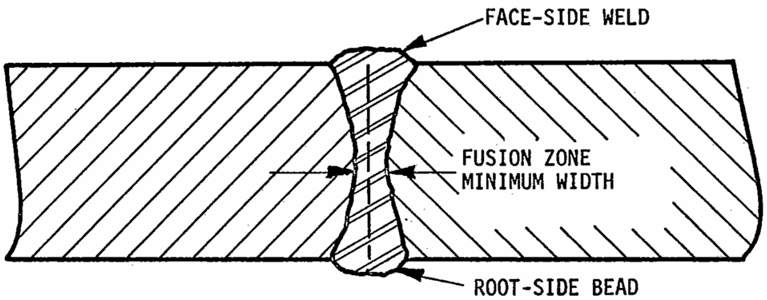
ALLOWABLE UNDERFILL (OR SUCKBACK) = MINIMUM POSTWELD MACHINING ALLOWANCE MINUS JOINT MISMATCH

= 0.080 (2.03) - 0.030 (0.76)

= 0.050 (1.27)

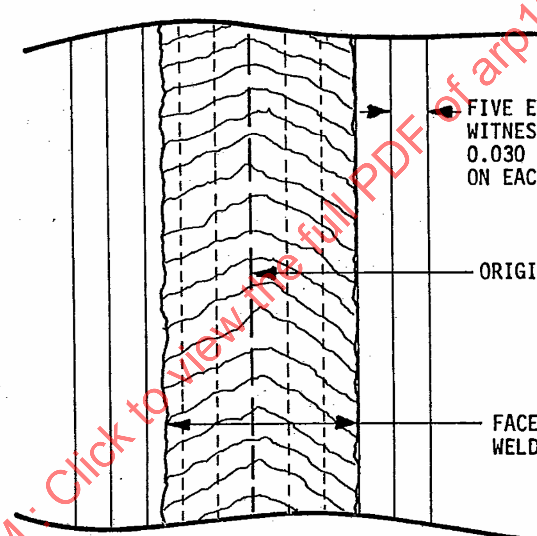
TYPICAL DIMENSIONS IN MEASUREMENT OF UNDERFILL (OR SUCKBACK)

FIGURE 4



EXAMPLE WHERE BOTH FACE- AND ROOT-SIDE WELD BEADS ARE WIDER THAN THE MINIMUM FUSION ZONE DIMENSION, WHICH MUST BE DETERMINED FROM METALLOGRAPHIC EXAMINATION OF REPRESENTATIVE PREPRODUCTION TEST SAMPLES

FIGURE 5

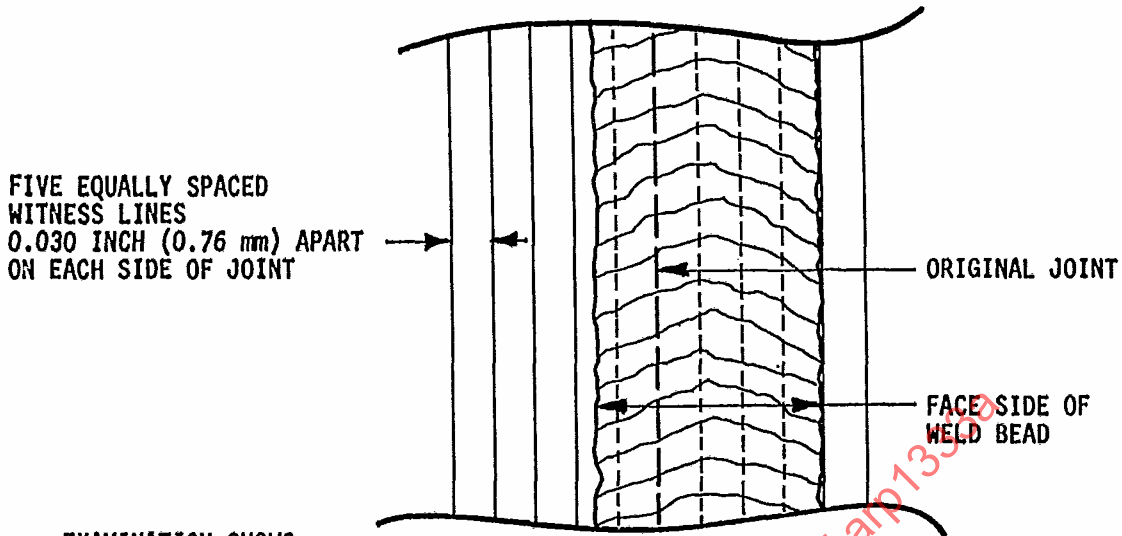


EXAMINATION SHOWS:

1. LEFT SIDE, 2½ VISIBLE SPACES; RIGHT SIDE, 2 VISIBLE SPACES
2. THEREFORE, WIDTH OF WELD BEAD IS
   5½ SPACES X 0.030 INCH = 0.165 INCH
   (5½ SPACES X 0.76 mm = 4.18 mm)
3. CENTRAL 1/3 OF WELD IS 0.055 INCH (1.40 mm) FROM EITHER EDGE
4. JOINT IS LOCATED WITHIN CENTRAL 1/3 OF VISIBLE BEAD
5. ACCEPT WELD

POSTWELD WITNESS LINE EXAMINATION - FACE SIDE (EXAMPLE A)

FIGURE 6



EXAMINATION SHOWS:

1. LEFT SIDE 3½ VISIBLE SPACES; RIGHT SIDE, 1 VISIBLE SPACE

2. THEREFORE, WIDTH OF WELD BEAD IS
   5½ SPACES X 0.030 INCH = 0.165 INCH
   (5½ SPACES X 0.76 mm = 4.18 mm)

3. CENTRAL 1/3 OF WELD IS 0.055 INCH (1.40 mm) FROM EITHER EDGE

4. JOINT IS NOT LOCATED WITHIN CENTRAL 1/3 OF VISIBLE BEAD

5. REJECT WELD

POSTWELD WITNESS LINE EXAMINATION - FACE SIDE (EXAMPLE B)

FIGURE 7