Welding Zircaloy Thin Tubes to End Plugs

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Abstract : This work aimed at optimizing parameters while welding Zircaloy-2 tubes with end plugs, as a simulation of a part of the fabrication of the nuclear fuel pins. Samples were welded by Tungsten Inert Gas arc welding (TIG) process under controlled atmosphere of pure argon. Some samples were welded using Electron Beam (EB) welding process.

For samples welded using TIG process both the design of the welding chamber (size and tightness), and the purity of the shielding atmosphere were found to have appreciable effect on the quality of the welded joint. Increasing the arc length and/or the welding current increases grain growth and extends both fusion and heat-affected zones. However, heat input (arc length and welding current) must be high enough to give complete penetration welds. Optimum arc length of 1.2 mm was found to give good welds with the smallest possible heat-affected zones.

Optimum parameters of EB welding process (vacuum, welding current and EB amplitude) were determined. Welds prepared by EB welding were found to have finer grain size and less extended fusion and heat-affected zones.

Welds prepared by both TIG and EB processes were inspected visually, metallographically and by using X-ray radiography. Welds integrity were tested using helium leak and pressure tests.

1. Introduction

In nuclear installations, high safety, which could be achieved by high component reliability, is required. Thus, appropriate production techniques have to be selected or developed for manufacturing critical components related to such installations. One of the most important and critical components is the nuclear fuel pins in power reactors. Typical fuel pins for light water power reactor (PWR and BWR) normally consist of 9-14 mm diameter thin walled zircalloy tubes filled with slightly enriched uranium oxide pellets. Two zircaloy end plugs are welded to the two ends of the zircaloy tubes. Fig. 1 shows the details of a typical nuclear fuel pin of light water reactors.

There are more than one welding technique which could be used for welding end plugs to Zircaloy tubes. Resistance welding have been successfully used in many cases.[1] Electron beam (EB) welding is another alternative.[2] However the most widely used welding technique is the Tungsten Inert Gas (TIG) arc welding.[3]

The gas shielding methods followed in welding using standard commercial tungsten arc torch is insufficient for welding Zircaloy fuel pins. Traces of air could be entrapped in the shielding gas stream and impair the corrosion resistance, as well as the ductility characteristics of the material. In order to retain the properties of the material, it is essential to increase shielding properties of the inert gas. This could be achieved by designing the torches with trailing shields, where the metal behind the weld pool is protected by using an inert gas behind the welding electrodes.[3] Also the back side of the weld can be protected using an inert gas back up. This is achieved by filling the tube with an inert gas under slightly positive pressure.

In welding nuclear fuel elements a welding chamber in the form of controlled atmosphere box could be used.[3–6] The normal procedure[7] is to evacuate the welding chamber to a pressure of about 3×10^{-4} mbar, then filling the chamber with helium or argon to a little higher pressure than the ambient pressure. The filling time is minimized to reduce contamination from microscopic leaks when the system is isolated from the vacuum pump. The pressure inside the chamber is kept contant during the welding by using an oil equalizing valve.

In the present work, Zry end plugs were welded to Zry tubes using both

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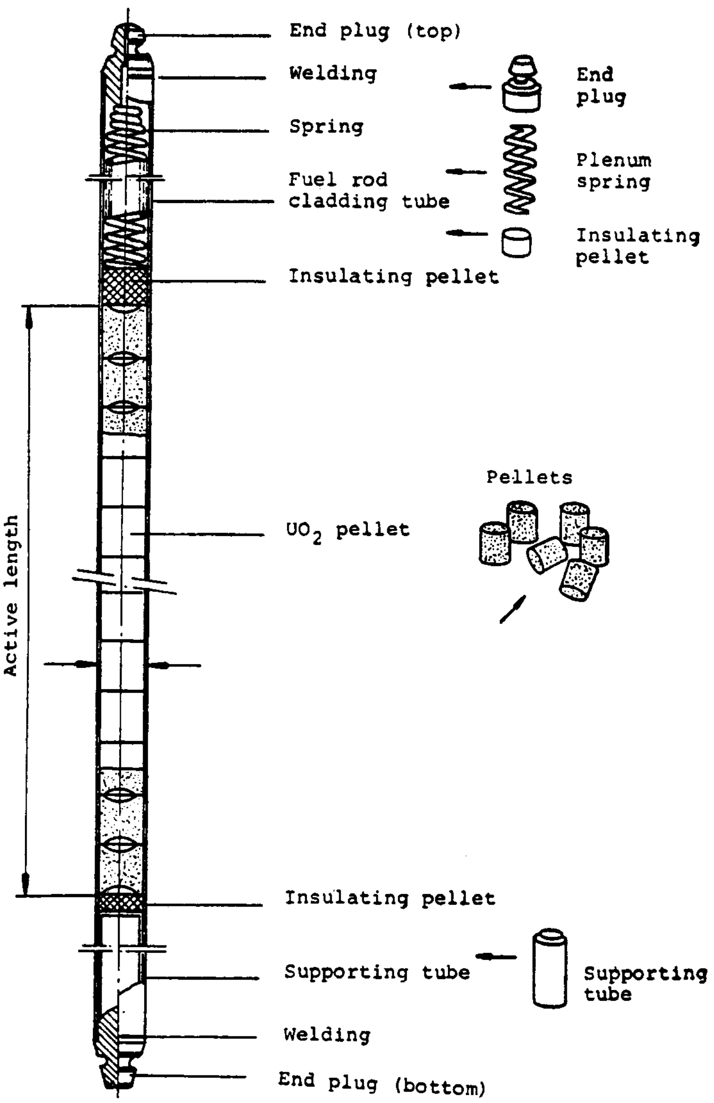


Fig 1. Internal structure of a fuel rod.

TIG and EB welding. Factors influencing weld quality were studied with special emphasis on the TIG welding technique. The effect of factors such as welding current, arc length and shielding atmosphere on the weld quality, was studied. Also, various inspection and testing methods were performed on the weld to determine its quality and integrity.

2. Experimental Techniques

Zry-2 tubes with 10.8 mm outer diameter and 1 mm thick were used.

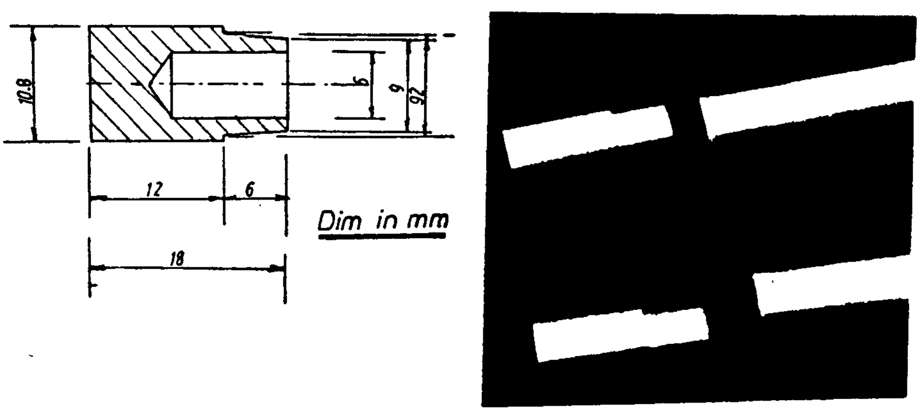


Fig 2. Zry tube and end plugs for experimental work.

Zry-2 rods with 10.8 mm diameter were used to fabricate the end plugs with the dimensions shown in Fig.2. The tubes and the end plugs were cleaned using acetone and alcohol before welding process.

Fig. 3 shows the apparatus used for welding tube assembly by TIG welding. The following welding procedure was used :

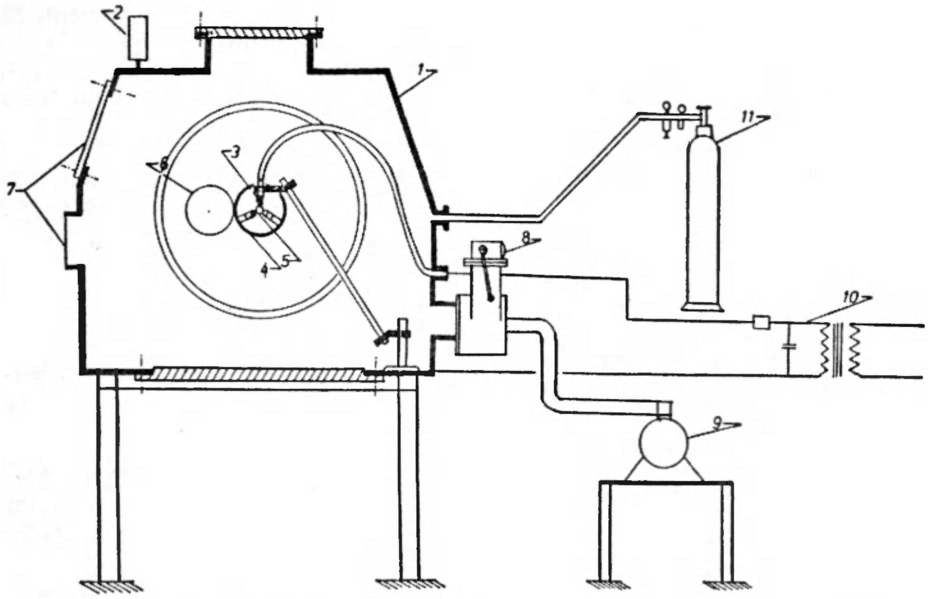
1. The welding chamber was evacuated to 4×10^{-4} mbar, then filled with pure argon (99.997%). The evacuation and refilling cycle was repeated three times.

2. The welding speed was adjusted to 8 mm/sec.

3. The arc length between the electrode and the welded tube was varied between 0.8 and 22 mm.

4. The welding current was varied between 30 and 100 amperes.

A high voltage triod electron beam welding apparatus (supplied by Heraus Co.), shown in Fig. 4, was used to perform the EB welding, Welding conditions are as follows :



1) Welding chamber 2) Pressure gauge 3) Tungsten electrode 4) Chuck 5) Specimen tube 6) Var. speed motor is engaged with the chuck 7) Glove port and window 8) Vacuum valve 9) Vacuum system 10) Transformer with H. F. Unit 11) Argon gas cyl.

Fig 3. TIG welding system with controlled atmosphere chamber

1. Vacuum: 8×10^{-4} to 6×10^{-6} mbar
2. Welding speed: 12-15 mm/sec
3. Welding current: 2.75 mA for the first pass and 1.8 mA for the second pass
4. Cooling times : the specimens left in chamber after completing the welding process were prolonged up to 30 min.

All welded specimens were inspected visually and radiographically. Some of them were subjected to pressure test and helium leak test. Macro and microscopic metallographic examinations for some metallographically prepared samples were performed.

3. Results and discussions

3.1 *TIG Welding*

The black oxide layer formed during welding was easily distinguished when the welding chamber entrapped any gas impurities. To obtain oxidefree welds, the welding chamber was evacuated to 4×10^{-4} mbar before filling in the inert gas.

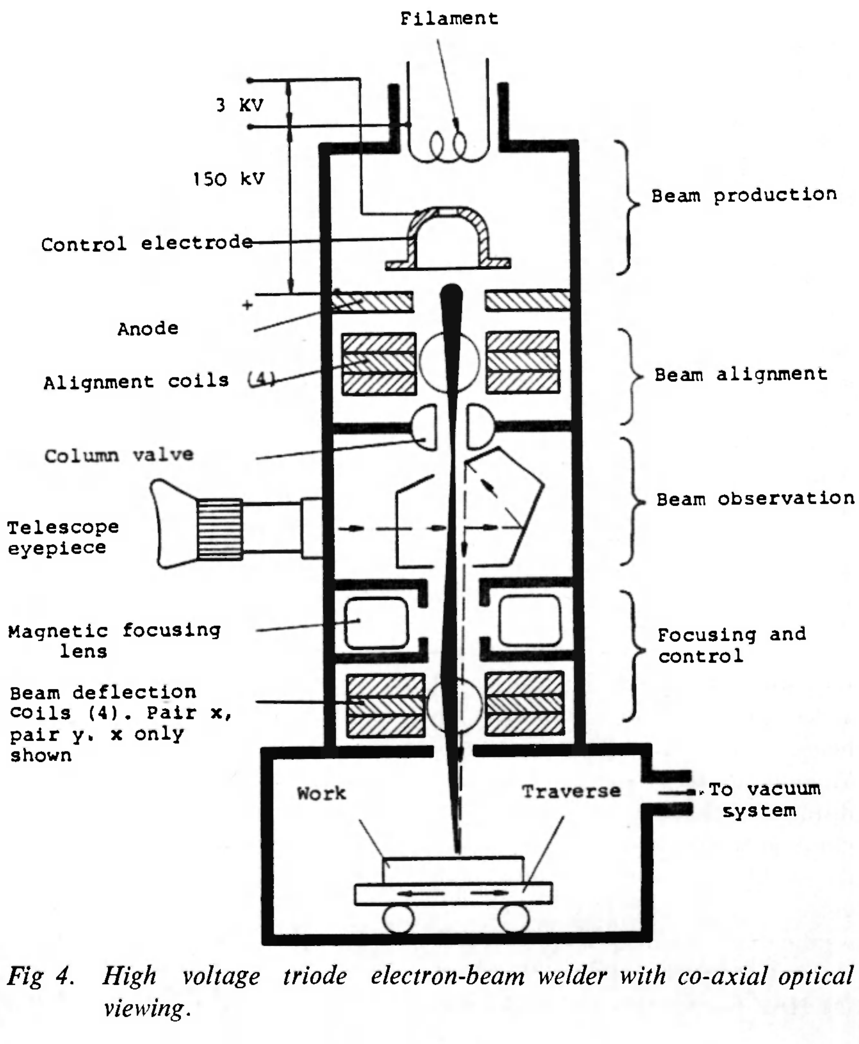


Fig 4. High voltage triode electron-beam welder with co-axial optical viewing.

Also, the evacuation and refilling cycle (cleaning cycle) was found to be importantly repeated for three times before the welding process is performed. One cycle at the mensioned vacuum level was found to be insufficient to get oxide-free welds. In general, the reliability of the welding chamber atmosphere depends on the purity of the shielding gas, the vacuum obtained and the design of the welding chamber.[8] Moreover, welding in vacuum is not recommended, since filling with inert gas is important for arc stabilization.[9]

Zry-2 is known to react rapidly at elevated temperatures with nitrogen and oxygen. It was reported that small amounts of both gases increases hardness and tensile strength, and lowers ductility.[7] Also, traces of nitrogen can affect the corrosion resistance of the metal. Joints welded in a shielding atmosphere with 0.1% volume percent nitrogen were contaminated sufficiently to decrease their corrosion resistance drastically at 315° C.[3-10]

The change of the arc length was found to affect the micro-structure and extend the fusion zone as well as the heat-affected zone (HAZ). It was observed that a longer arc length yielded extensive grain growth. Also, increasing arc length from 1.2 mm to 2 mm was accompanied by an increase in the length of the fusion zone from 3 mm to 4.8 mm.

Also, increasing the welding current which increases the heat input affects the microstructure of both fusion and heat-affected zones. Welding at 100 A yielded a severely distorted welded junction. Excessive grain growth was also observed in the welds performed at this high current (Fig. 5a). Decreasing the welding current from 50 A to 40 A showed a decrease of the length of the HAZ from 5 mm to 2.5 mm. The welding current of 40-45 A was found to be the optimum current that gave a good weld with the smallest HAZ.

Visual inspection was found to be a good tool to inspect the welded joints and to control and optimize welding parameters. Discoloring of the welded joints could be due to either high impurities in the shielding gas, insufficient cleaning cycles or leakage in the welding chamber. Distortion of the joint could be due to either high welding current or long welding arc.

The following welding conditions yielded acceptable welds :

Cleaning cycles	3 cycles
Welding current	40-45 A
Arc length	1.2 mm
Welding speed	8 mm/sec

3.2 *Electron Beam Welding*

The EB welding process was performed in two passes using a voltage

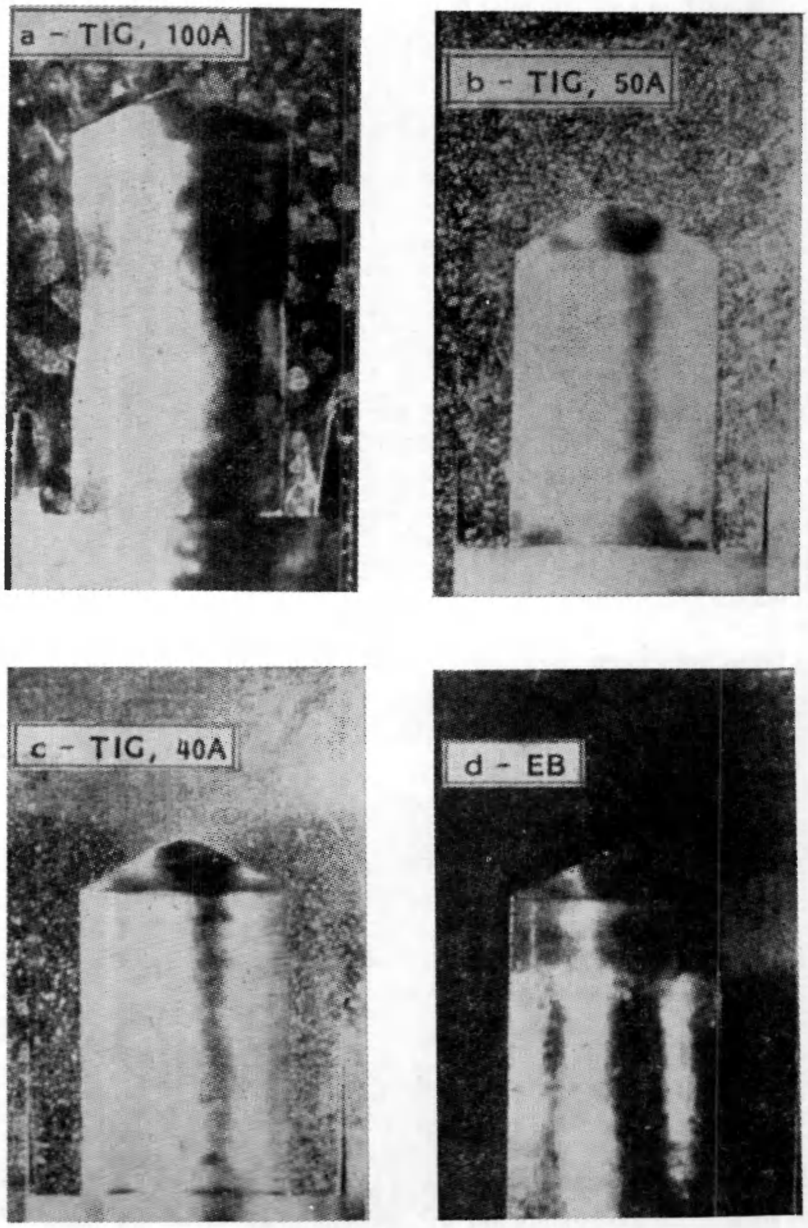


Fig 5. Effect of Heat Input on the HAZ and Grain Size.

of 120 KV. Table 1 summarizes the welding parameters at which three joints were prepared.

Table 1

Joint No.	Vacuum mbr,	Speed, mm/sec
1	8×10^{-4}	12
2	6×10^{-6}	15
3	6×10^{-6}	15

	Amplitude, $\times 100$		Current, mA	
	1st pass	2nd pass	1st pass	2nd pass
1.	0.5	10.7	2.75	1.8
2.	,,	,,	,,	,,
3	,,	,,	,,	,,

Specimen No. 1 showed the presence of an oxide layer. Increasing the vacuum level to 6×10^{-6} mbar (specimens 2 and 3) decreased weld discoloring. The welded joint with the best quality was obtained when the welded sample (No. 3) was cooled down after welding for 30 min. under the vacuum in the welding chamber.

Kalish[2] found that the strength and ductility of EB welded joints are relatively higher compared with joints prepared by TIG welding. In addition, EB welding gave the advatanges of smaller width of the weld bead and HAZ, deep weld penetration and minimum distortion of welded joints.

3.3 *Inspection of Welded Joints*

As mentioned previously, visual inspection could be considered as a reliable tool to control welding parameters of both welding processes used, namely TIG and EB welding. This could be attained by the visual assessment of the weld color, width of the weld bead and width of the HAZ. Moreover, in some practices[10] together with visual inspection, a specific percent of the welded fuel rods, may be checked by any of the oxidizing treatments, e.g., autoclaving treatment at 400°C in steam.[7] This treatment should result in an uniform shiny black skin of oxide after 1-2 days of treatment. Excessive nitrogen content in the weld may result in grey discoloring.

X-ray radiography is recommended as a good inspection tool for inspection of welded fuel pins.[10] Welded fuel pins with their small diameter and thin clad requires a high resolution radiographs.[11] In the present study, radiographs with high resolution were obtained using the following parameters :

Tube voltage	142 KV
Filament current	15 mA
Exposure time	2 min
F.F. distance	800 mm

Blind end plugs raised problems in X-ray radiography due to the variation of the penetrated thickness at the middle of the weld and at the outer ends. To avoid this thickness variation end plugs with drilled holes in centerlines were developed (see Fig. 2), Predominant defects found in the fusion zone were lack of penetration, porosity and cavity formation. Most of these defects were found in welds prepared by TIG welding.

Helium leak measurements were performed on welded samples prepared by TIG or EB welding. It was found that the leak rate is 1.3×10^{-10} mbar lit/sec. This is in the range of acceptable limits according to some practices.[8]

Pressure test using high water presure pump was performed on one random TIG welded specimen. 600 kg/cm^2 was applied to the welded joint without any appreciable deformation. Afterwards, the specimen was subjected again to the helium leak test. The leak rate was the same as obtained before (1.3×10^{-10} mbar lit/sec).

Macroscopic and microscopic examination of the longitudinal section of welded assemblies was performed. Fig. 5 shows the effect of the welding current on the grain size and the extent of the HAZ. Deformation of the end plug was also observed upon welding at high welding current (Fig. 5a). The HAZ is much less extended in welded joints prepared by electron beam welding as shown in Fig. 5d.

Typical microstructure of welded joints is shown in Fig. 6. The structure of specimens welded by either TIG or EB is typical Widmanstaten structure of quenched beta phase which is a result of rapid cooling from the molten phase. It could be observed that the grain size of the TIG welded specimens is much higher than those prepared by EB.

Fig. 7 illustrates some weld defects which were detected by metallographic examinations. These include lack of penetration and void formation. The same defects were identified by X-ray radiography.

4. Conclusions

4.1 High Quality TIG welded Zry-2 tube-end plug joints could be obtained upon adjusting the following parameters :

1. The efficiency of the welding chamber which depends on the purity of the shielding gas, vacuum level and the design of the welding chamber.
2. The welding current and arc length, to give full penetration welds without excessive heat input.

4.2 Visual inspection is a good and reliable tool to give an idea about weld quality. Even with other nondestructive testing methods, visual inspection still constitutes an important part of practical quality control.

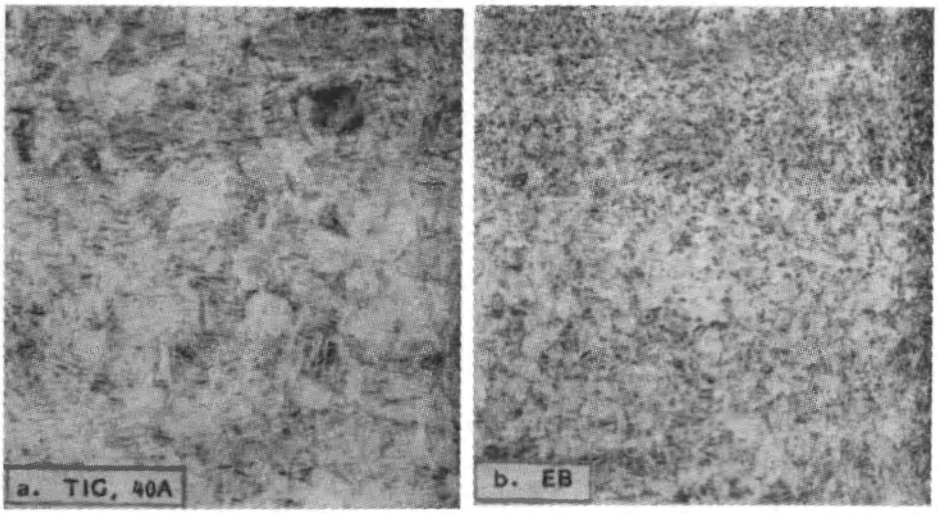


Fig 6. Microstructure of the HAZ of specimens. welded using (a) TIG and (b) EB Welding technique.

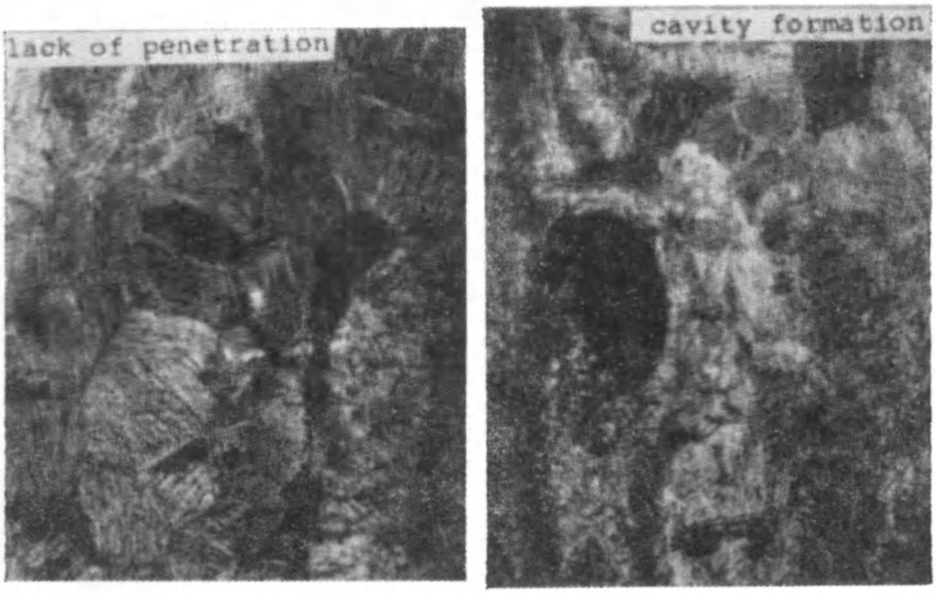


Fig 7. Some defects detected in TIG welding joints.

4.3 EB welding gives finer grain size and less extended fusion and heat-affected zones, compared with TIG welding process.

4.4 Typical defects found in welded joints were : lack of penetration, porosity and cavity formation.

Acknowledgment

This work had been performed during the delegation of one of the authors (M.A.S.) to KFA-Julich, F.R. Germany, under a bilateral joint research and development project between AEE-Cairo and KFA-Julich.

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