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EXAMINATION OF WELD DEFECTS BY COMPUTED TOMOGRAPHY

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Defects in metal arc gas (MAG) welds made in S235JR low carbon steel of 6 mm thickness were examined. A sample containing lack of fusion (LOF) and pores was examined by computed tomography – CT. The computed tomography examination was performed in order to define LOF size and position as well as dimensions and distribution of accompanying pores in the weld metal.

Key words: MAG welding, LOF, computed tomography (CT), tomograph, porosity

Ispitivanje grešaka zavara kompjutorskom tomografijom. Ispitivane su greške u zavarenom spoju niskougljičnog čelika S235JR debljine 6 mm zavarenog MAG postupkom. Uzorak koji sadrži greške naljepljivanja i pore je ispitivan kompjutorskom tomografijom - KT. Programskom analizom tomografa je određena veličina i pozicija grešaka naljepljivanja kao i dimenzije i raspored pratećih pora u zavarenom spoju.

Ključne riječi: MAG zavarivanje, naljepljivanje, kompjutorska tomografija (KT), tomograf, poroznost

INTRODUCTION

Lack of fusion is a surface defect of a welded joint extending along the weld or on the boundary between individual weld beads due to incomplete metal fusion. LOF can occur in different materials; however, it is most frequent in steel welds. Molten filler material only sticks to the groove face or to the previous weld bead. In such places, the material cohesion is interrupted which results in a reduced load-bearing cross-section. A LOF is a hidden defect which becomes extremely dangerous at dynamic loading of welded structures since it represents an ideal initiator of a crack. The most often cause of a LOF is an incorrect selection of welding parameters or a welder's mistake. The LOF occurrence due to welding technology is most often ascribed to an unsuitable preparation of a weld groove, to an incorrect inclination of a gun, to un unsuitable welding position and to the arc blow due to a magnetic field [1]. The second group of LOF causes includes an insufficient energy input into the weld. It has been proved, though, that the welding parameters selection, such as intensity of welding current, wire feed rate and wire stick-out length are highly important as well [2]. Welding speed has the highest impact on the energy input [3]. A too high welding speed provides minor energy input to a unit of the weld length which results in insufficient fusion of parent material, greater LOF risk and lower quality of weld metal [4, 5]. On the other hand, a too low welding speed allows higher energy input to a unit of the weld length. The resulting molten pool is too big and overtakes the arc, disabling it to provide correct fusion of parent material. The molten pool of the filler material can oxidize on the surface so that LOF can occur as a result of puckering while pores and/or non-metal inclusions can occur as well.

The specimen for macrographic examination shows inclusions and pores caught between parent and filler materials [6-11]. There is no evidence of porosity and LOF connection in literature. However, research shows that porosity and LOF can be connected. Kou and Wang established that weld porosity mainly depends on the weld pool development mode [12]. LOF can be detected by different techniques of ultrasonic and/or radiographic examination.

EXPERIMENTS

The experiments were performed in the following steps: welding in a trough, performance of specimens for macrographic examination, computed tomography of samples, computer processing of tomograms using adequate tools. The main purpose of the examination was to find out whether defects such as LOF and pores inside a weld metal can be detected by computed tomography. A narrow gap between weld pieces was selected. A small angle prevented uniform melting of both weld pieces which resulted in a LOF. The LOF was confirmed by a specimen for macrographic examination (Figure 1). Further investigations were directed to the assessment of the LOF type, size and form as well as to the presence of pores which accompany the LOF in a weld metal. Then, the tomograms were analyzed by rel-

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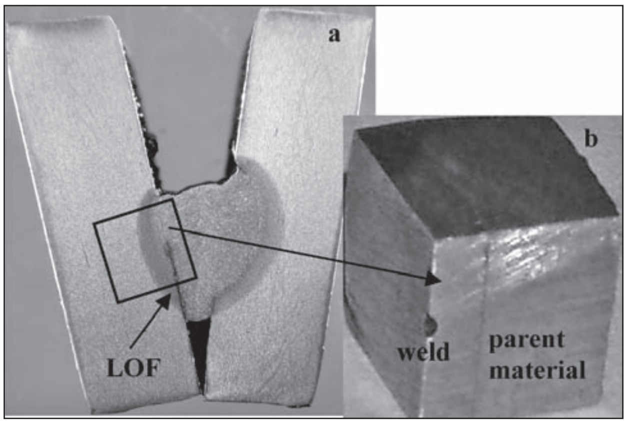

Figure 1 Specimens preparation: a) specimen for macrographic examination, b) test specimen for CT

evant computer programs. VGI program served to capture individual images which were processed by Image Tool. In this way, size and profile of the LOF and distribution and size of pores in the vicinity of the LOF were measured.

MAG welding was performed in forward direction. A fillet weld (FW) was made at an angle of 21° between the weld pieces made of S235JR structural steel according to EN 10025-2, thickness 6 mm. The steel sheet was 20 mm wide and 100 mm long. Welding parameters were as follows: current intensity 240 A, voltage 24 V, welding speed 6,6 mm/s, filler wire feed rate 114 mm/s, wire stick-out length 20 mm, angle of blowpipe inclination 76°. Filler wire was of G3Si2 type and 1,2 mm diameter. Shielding gas was a mixture of 82 %Ar+18 % CO_2 with a flow of 15 l/min.

Computed tomography is a new non-destructive testing method recently recognized especially in detection of anomalies in metal industry products. Performance of three-dimensional images by micro-focus computed tomography starts with two-dimensional images of a test specimen segment projections developed by gradual rotation of the test piece within the range of directed X-rays. The test piece rotation shall be performed gradually at a rotational angle of less than 1° as long as the specimen is radiated from all sides.

Due to a limited radiation power several specimens with irregularities had to be cut out from the existing welded joint in form of a cube with a 5 mm side. The cutting position is given in Figure 1a, while the test specimen is given in Figure 1b. Afterwards, the specimens were examined by computed tomography – CT. For this purpose, the NANOMEX CT system of Phoenix X-ray Company was used. The system consists of a 160 kV nanofocus X-ray tube and a 16–bit detector with voxel accuracy of 16 μm. Radiation of test pieces was performed at the tube voltage of 140 kV and current intensity of 70 μA. Possibility of details resolution ranged within (200 – 300) nm. The X-ray tube power was 50 W.

By use of ***my VGI*** 1,2 dedicated program for data visualization and documentation in form of voxels tomograms representing one hundredth millimeter of a weld metal were obtained. Based on EN 12517 standard and by use of the ***Image Tool*** program a bright-dark contrast comparison was made which proved how the porosity amount in the molten pool changed with moving away from the LOF surface, and how far pores were extending into the molten pool.

RESULTS AND DISCUSSION

Angle and depth of a weld groove are important LOF parameters. In case of smaller angles, a narrow gap prevents a proper access of the weld gun into the root of the weld. So the arc starts burning on the nearest face of the groove which was proved by Sony DCR-TRV740E digital camera recording on an 8 mm tape with a frequency of 25 snapshots/s. The molten mixture of parent and filler materials pours to the other face of the groove which prevents melting of the parent material in this part of the joint and results in a LOF in the lower part of the weld metal (Figure 1b).

The results of CT examinations are given in Figure 2, which shows a 3D image and three projections of a test specimen with a clearly evident LOF and pores. Frontal image (2a) gives a LOF well evidenced along the whole length as well as its width change. Figure 2b is a tomogram of the surface where the LOF passes into porosity. Numerous pores of different shapes and sizes are visible. This image represents the basis of a geometrical analysis of the LOF and porosity.

Figure 2c shows the specimen from the top. The LOF and the accompanying pore are well evident. This view served for the profile of the LOF along the weld metal length. Figure 2d is a 3D image of the specimen.

Figure 3 gives tomograms of a 3D CT image projection in different sections made from the direction perpendicular to the LOF plane. Dark surfaces decrease with moving away from the LOF plane (from I to III).

As it can be seen from the CT images, the LOF is well limited in space. So we can say that this is a plane

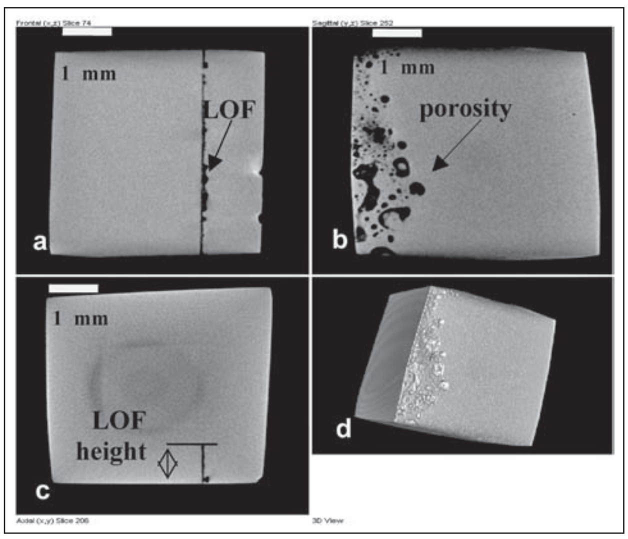

Figure 2 Specimen image made by computed tomography: front (a), side (b), top view (c) and 3D image (d)

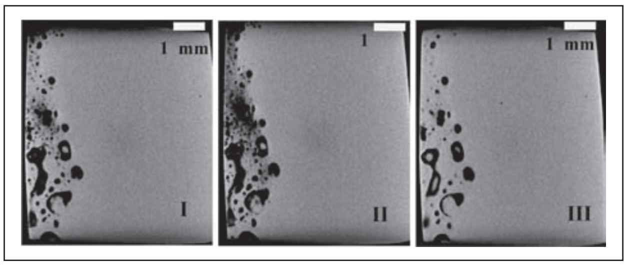

Figure 3 Projection on LOF plane

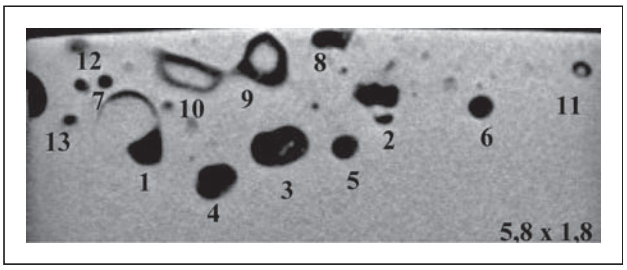

Figure 4 Dimensional analysis of porosity area (pores are numbered from 1 to 13)

defect. By VGI program it was established that the width of this LOF was 0,1 mm. In sector images it can be seen that a great number of pores of different sizes and shapes are arising from the LOF area. All these pores are directed from the LOF plane to the molten pool which is another indirect proof that the parent material is not melting there. The tomogram section (Figure 3) gives an analysis of the pores diameter, cross section and length.

The analysis was performed in a rectangle of 5,8 x 1,8 mm given in Figure 4 which represented approximately one fourth of the weld surface. Total height of the weld cross-section was 7,2 mm. Inside the rectangle, the share of the image darkness was measured in each individual section whereby the darkness represented an empty space (LOF or porosity). As it is evident from Figure 5, empty spaces (dark surfaces) were mostly found in the area of LOF at a distance of 0 to 0,1 mm, where the darkness share reached more than 40 %.

At a distance of 0,1 to 0,2 mm, the porosity or darkness share decreased from 20 % to 5 %. In this area the majority of pores disappeared. It is interesting that individual pores can reach into the molten pool even as far as 0,6 mm away from the parent material where the LOF occurred. Figure 5 gives a scheme of the LOF plane location with directions of individual axes which shall contribute to relevant understanding of LOF image analysis. In further tomograms analysis the top view given in Figure 3 was applied.

For each section, the LOF height as per weld length has been measured. In this way the LOF profile between the parent metal and the molten pool has been obtained (Figure 6). As it is evident, the LOF reaches up to 1,6 mm of the weld height at the most and up to 0,3 mm of the weld height at the least. Above the given line, full penetration with dilution of parent and filler materials occurred while under this line weak dilution resulted in a LOF. The size of pores accompanying the LOF, their

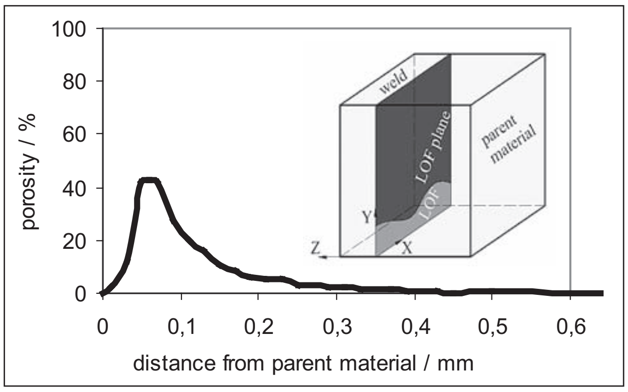

Figure 5 Change in porosity as per weld section

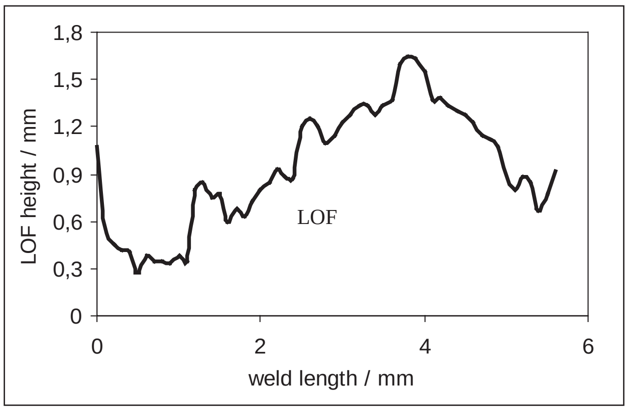

Figure 6 LOF profile between the molten pool and parent material

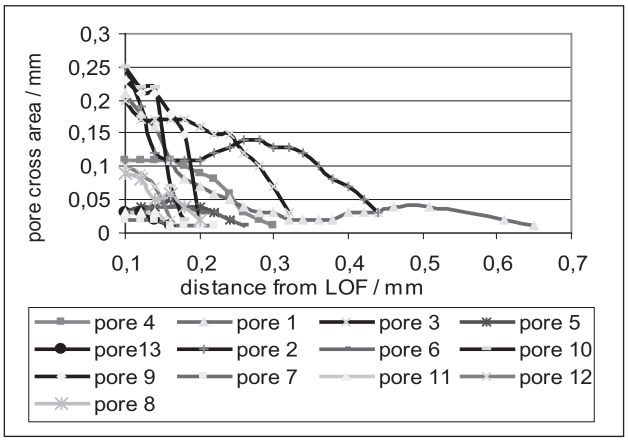

Figure 7 Size of pores inside a welded joint

reach into the weld and their distribution within a weld section were established as well.

For this analysis, weld metal section images (parallel to the LOF plane) from the Figure 2 were used. Such tomograms are given also in Figure 3. Surface and diameters of all well distinguished pores in different sections inside the weld metal have been measured by moving from inside of the weld metal toward LOF. Since pores are spatial defects, the most relevant data for the examination consist of their cross-sections at specific points. The diagram in Figure 7 gives the cross-section changes in relation to the distance from LOF. 13 well defined pores that reach more than 0,05 mm in length were examined. They are given in Figure 4. In some cases the pores' cross-section is decreasing with length while in the others, the diameter or cross-section even increases. Moreover, the pores direction through the molten pool is changing as well. Some of them change their cylindrical shape and insert into the molten pool in form of a ring.

Based on an average cross-section, the pores are classified into three groups:

a) Pores with a cross-section greater than 0,2 mm^2. They were 5 of them altogether. 3 of them reached more than 0,3 mm into the weld metal. The remaining two were shorter than 0,2 mm.

b) Pores with a cross-section of 0,1 mm^2. They were 3 altogether. One of them reached more than 0,3 mm into the weld metal. The remaining two were shorter than 0,2 mm.

c) Pores with a cross-section smaller than 0,05 mm^2. They were 5 altogether and they were of different lengths; however, they were all shorter than 0,3 mm.

As it is evident, only pores with an initial cross-section above 0,2 mm^2 can reach a more explicit length (above 0,3 mm). Pores with a smaller initial cross-section are shorter than 0,25 mm.

CONCLUSIONS

In MAG welding of low-carbon steel structures porosity and LOF occur quite often. It has been established that LOF and porosity are usually mutually connected.

– A very detailed 3D analysis of LOF and porosity in the weld metal can be made by computed tomography.
– Tomograms projections enable specimens' analysis from different directions. It has been proved that incompletely fused parent material results in LOF which proceed in the direction of fused parent material to transform into pores.
– Further tomograms analysis by use of adequate computer software enabled to establish the LOF profile in the weld metal section or the line separating the fused part of the weld from the infused one.
– The amount of incompletely fused material inside the weld metal has been established together with the percent of the empty space within a weld metal formed together by the LOF and porosity. The measured LOF thickness, without pores arising from the LOF, amounts to 0,1 mm.
– It has been concluded that regarding the cross-section size there occur three groups of pores; however, only those with an initial cross-section above 0,2 mm^2 reach significantly into the weld metal depth.
– Computer tomography represents a very reliable and accurate non-destructive testing method for analysis of inner defects in metallic materials. For the time being, the only limitation lies in the size of test specimens.

LITERATURE

[1] Causes for Weld Defects, IIW Doc. XII-B-046-83, International Institute of Welding, 1983.
[2] Gas-Shielded Metal-Arc Welding of Steel, IIW Doc. XII-B-049-83, International Institute of Welding, 1983.
[3] Killing R., Hantsch H., Beitrag zur Frage der Bindefehlerempfindlichkeit beim Metall-Aktivgasschweißen mit Fülldrahtelektroden, Schweißen und Schneiden, 45 (1993) 12, 34 - 41.
[4] Jovanovic M., Rihar G., Grum J., Analysis of Ultrasonic Indications in LOF Occurring in Welds, Proceedings of the 9th ECNDT, Berlin, 2006.
[5] Yamauchi N., Inaba Y., Taka T., Formation Mechanisms of LOF in MAG Welding, IIW Doc. 212-529-82, International Institute of Welding, 1982
[6] Rihar G., Uran M., LOF - Characterisation of Indications, Welding in the World, 50 (2006) 1/2, 35-39.
[7] Buschke P., Roye W., Dahmen T., Multiple NDT methods in the automotive industry, GE Inspection Technologies, Huerth, 2000.
[8] Samardžić I., Mateša B., Kladarić I., Metalurgija, 50 (2011) 3, 145 – 216.
[9] EN 12517-1:2006 Non-destructive testing of welds – Part1: Evaluation of welded joints in steel, nickel, titanium and their alloys by radiography- Acceptance levels.
[10] Muhič M., Tušek J., Kosel F., Klobčar D., Pleterski M., Metalurgija, 49 (2010) 1, 9 – 12.
[11] Kosec B., Kosec L., Kopač J., Engineering Failure Analysis, 8 (2001) 4, 355-359.
[12] Kou S., Wang Y.H., Weld Pool Convection and Its Effect, Welding Journal, 65 (1986) 3, 63 -70.

Note: The responsible translator for English language is Lelja Vidan, prof., Welding Institute, Ljubljana.