PRELIMINARY RESULTS IN THE USE OF SYNCHROTRON RADIATION FOR SMALL CRACKS AND DEFECTS INVESTIGATION IN AA FSW SAMPLES

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Resume

A very good definition of defects position and dimension in welded joints is desirable for application of fracture mechanics techniques and improvement of industrial acceptability criteria. This paper illustrates the preliminary results obtained in the investigation of defects in aluminum welded joints at SYRMEP beamline of the Elettra synchrotron radiation facility in Trieste (Italy). The novel PHase Contrast (PHC) imaging technique consents a definition of the defects better than the one achievable with conventional welded joints control methods such as ultrasonic techniques, acoustic emission and radiography.

1. Introduction

Conventional fusion welding of some aluminum alloys (2xxx and 7xxx alloy family) is generally regarded as a difficult task, whether MIG, TIG , PAW, EBW and laser technology are adopted.

An interesting alternative is the solid state Friction Stir Welding (FSW), a recently developed technique, which is of major interest in joining thin and difficult-to-weld materials. In fact, it does not involve some of the problems of conventional fusion welding techniques. It is characterized by a low process temperature and no cast microstructure is created. As a consequence, the quality of the obtained weld is very high, no pores are present and the material structure is uniform. However, small, tight defects may be generated in the process, and they are very difficult to detect due to their dimension and/or position.

A very good definition of defects position and dimension in welded joints is desirable from several points of view [1-4].

In fact, mechanical strength prediction techniques have been developed, but their application requires a defect definition, which is higher than the one achievable with conventional welded joints control methods such as ultrasonic techniques, acoustic emission and radiography.

Improvement of industrial acceptability criteria depends both on the verification of the defects visible with conventional techniques and the determination of the relationship between the residual life and the defect geometry, which in turn require a high definition of the defect dimension and position.

Moreover, while fracture mechanics is a well-established technique for relatively long cracks, very little is known at the moment relatively to the early development of small crack, that is the transition phase from the onset stage to the propagation stage of the crack growth. The assessment of fracture mechanics techniques for small crack problems depends strongly on a high definition of defect location and geometry.

In order to overcome these problems, we started to investigate whether a good definition of defects position and dimension was achievable using the novel phase sensitive imaging techniques available at SYRMEP beamline, Elettra.

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2. Phase Contrast radiography

Synchrotron Radiation (SR) is produced when electrons travelling at relativistic speed are deflected by magnetic fields. Its energy spectrum covers a wide energy range, from the visible light up to hard X-rays. The SR peculiar characteristics of high brilliance and coherence make it a powerful tool of investigation in different research fields, from biology to materials science.

When X-rays interact with any kind of materials, there occur absorption and phase shifts effects. Conventional X-ray radiography relies on the absorption properties of the sample. The image contrast is produced by a variation of density, a change in composition or thickness of the sample and is based exclusively on the detection of an amplitude variation of X-rays transmitted through the sample itself. Information about the phase of X-rays is not considered. The main limitation of this technique is the poor intrinsic contrast in samples with low atomic number (i.e. the case of "soft matter") or, more in general, in materials with low variation of absorption from point to point.

If X-rays have a high spatial coherence - as for third generation SR sources - contrast may be originated by the interference among parts of the wavefront that have experienced different phase shifts through the sample (Fresnel diffraction). In the energy range of 15-25 keV, the phase shift contribution can be up to 1000 times greater than the absorption one, and allows the detection of the phase effects even if the absorption contrast is low.

Among the different techniques available for phase-sensitive imaging [5], the PHase Contrast (PHC) radiology setup is the same of conventional radiography with the difference that the detector is positioned at a certain distance *d* from the sample The choice of *d* depends on the size *a* of the feature to be identified, measured perpendicularly to the beam direction. In the edge detection regime ($d << a^2/l$, where *l* is the X-ray wavelength), images can be directly used to extract morphological information. Larger values of d lead to the holography regime ($d \approx a^2/l$), and have not been used here. In the images, the Fresnel diffraction pattern appears superimposed to the absorption contrast and contributes strongly to enhance the visibility of the edges of the sample features.

For our experiments we used the SR available at the SYRMEP beamline of the Elettra light source, a monochromatic X-ray beam with energy tunable between 8.3 keV and 35 keV. The sketch of the beamline is shown in Fig. 1: the white beam is produced in a Bending Magnet (BM) and is collimated by a first slit system.

The beamline optics is based on a double-crystal Si (111) monochromator. At a distance of about 23 m from the source, the beamline provides a monochromatic, laminar-section X-ray beam that impinges the sample in a 150x4 mm2 maximum area. The sample-to-detector distance *d* can vary from 0 m to about 2 m. The beamline is equipped with high resolution motion stages for the scan of both samples and detectors through the laminar X-ray beam.

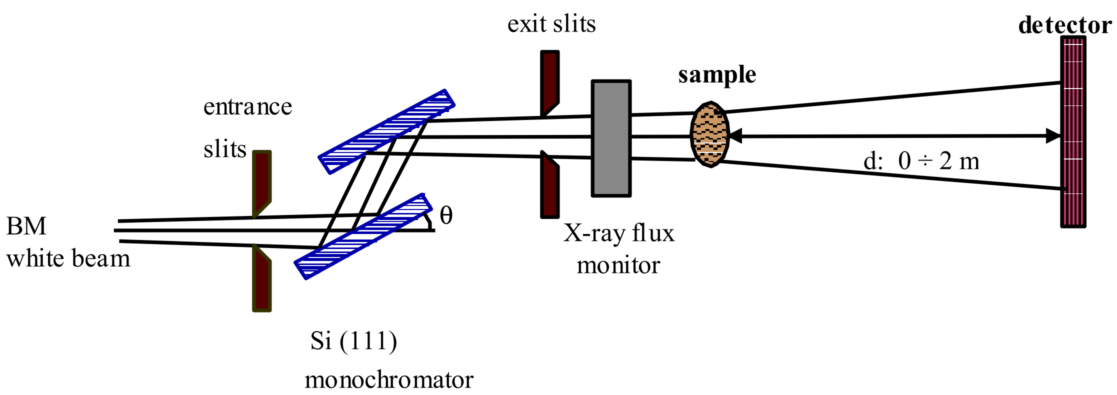

Fig. 1. Sketch of the SYRMEP beamline

Images taken with $d = 0$ reproduce the conventional absorption radiographs. The different regimes of PHC technique are obtained with $d > 0$.

3. Materials and Methods

Three sets of experiments have been performed so far.

The aim of the first one was to investigate feasibility and to optimize the experimental set-up (selection of the X-ray energy, choice of the sample-to-detector distance, evaluation of the exposure times, etc.). In this phase samples of 5 mm to 10 mm thickness welded joints with artifact flaws were analyzed. A good definition of artefact defects on aluminium joints, with both conventional and FSW techniques, was obtained by means of PHC radiography. The detectors used for this experiments were a water cooled 16-bit CCD camera (2048x2048 pixels^2) with 14 μm pixels size (≈ 25 μm spatial resolution) and X-ray films with a spatial resolution of about 1 μm.

Successively, we focused on the Friction Stir Welding technique, which is currently the more interesting also from an industrial point of view. We prepared 20 6xxx FSW samples with equal dimensions (thickness 4 mm, maximum area for investigation 28 mm width x 100 mm height,) and got PHC images of all of them in order to detect any original flaw.

Since the maximum useful height of the beam at 27 keV is around 3 mm, the whole radiography of each sample was obtained by scanning the sample itself in a sequence of succeeding positions through the beam.

Afterwards, 4 of the samples were loaded at the University of Ferrara with different number of fatigue cycles in the range of small crack growth. Once completed the loading, the samples were run again at Elettra. With this procedure, we expected to detect the early onset of fatigue defects at different stages of the samples lives.

The main drawback of this experimental approach was the large amount of time required to produce images of the entire sample since it was not possible to establish a priori preferred regions were cracks could be located.

In the last available shifts, the problem of the crack growth was addressed again. In order to overcome the problems previously encountered, two of the samples that had not been loaded during the previous experiment were prepared with notches before loading. A high stress concentration was therefore obtained at the notch, so that not only the crack localization was known, eliminating the need to scan the whole sample looking for the cracks, but also the crack growth was favoured.

4. Results and Discussion

A good definition of artifact defects on aluminum joints, both conventional and FSW techniques was obtained by means of the PHC radiography. Both CCD detector and high-resolution X-ray films were employed as detection systems. Some examples are shown in Fig. 2 and 3.

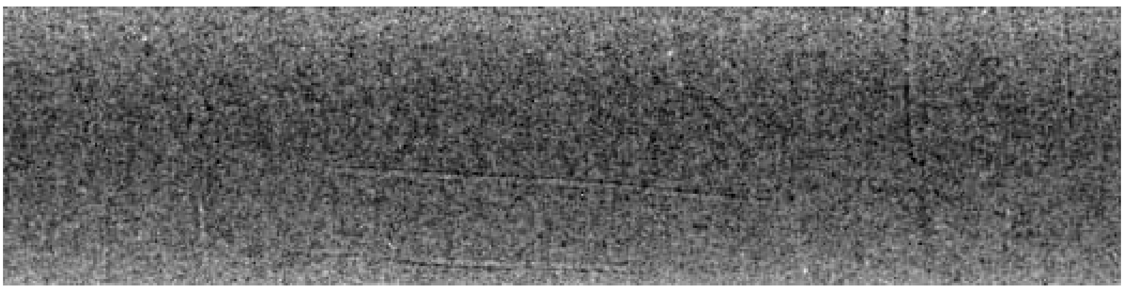

Fig. 2. Phase contrast, CCD detector: orthogonal scratches on a polished aluminum surface

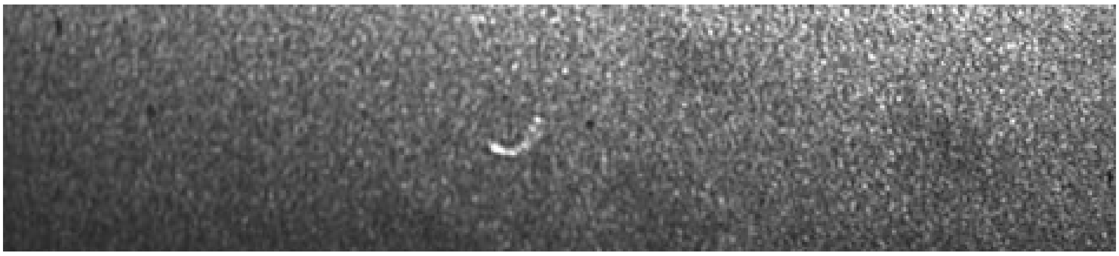

Fig. 3. Phase contrast, high-resolution X-ray film: an inclusion inside a FSW sample

The application of another phase-sensitive imaging technique, the Diffraction Enhanced Imaging (DEI) technique [6] for defects detection was also explored. The images showed the effectiveness of this technique. An example is given in Fig. 4. The large black marks are references kept in place by tape (darker rectangular zone). The limit of the weld process zone is clearly visible below.

The use of this technique will be considered again in a future, when a more flexible and user-friendly experimental set-up will be available at the beamline.

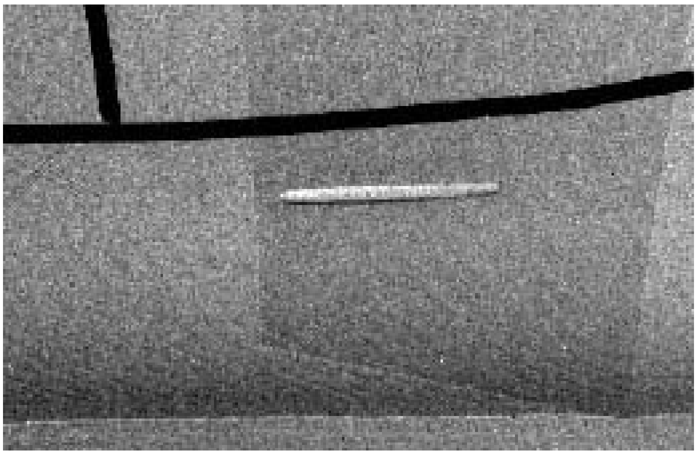

Fig. 4. Large mark scratch on a FSW surface.

Unfortunately the FSW samples prepared for the second experiment showed a higher mechanical resistance than expected, so that no small cracks were found. Nevertheless, some original very small flaws, hardly detectable by means of conventional techniques, were visible in both the original and the stressed samples, as shown in Fig.5 and 6.

In the pictures, obtained with the standard optics CCD detector, flaws with higher absorption than aluminum were detected. The flaw extension is about 1.5 mm in Fig.5, while the maximum dimension of the defect visible in Fig.6 is about 0.35 mm. The investigation of these small defects will provide a new unique insight on the defects that can be found in FSW samples and will be the object of further studies. Also the characteristic features of FSW, the circular marks left by the tool motion and the limits of the weld process zone, are clearly visible in both pictures.

Fig. 5. PHC radiography of sample 1, CCD detector with standard optics. Flaw extension is about 1.5 mm.

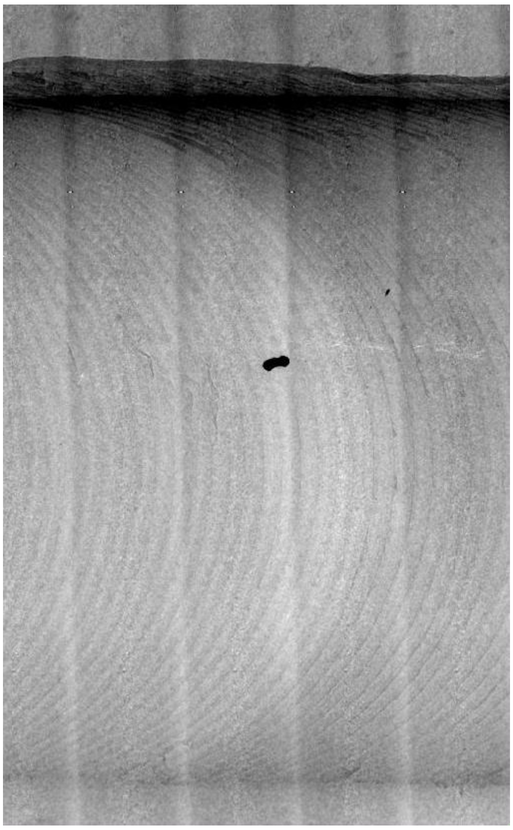

Fig. 6. PHC radiography of sample 1, CCD detector with standard optics. Flaw extension is about 0.35 mm.

In the last experiment, the samples that had not been loaded during the previous experiment were prepared with notches before loading, in order to facilitate the onset of the crack in a specific region. The most interesting preliminary results are shown in Fig 7 and 8, where both a long crack with a maximum extension of about 3.5 mm and a small crack of about 0.7 mm could be detected on the two sides of the notch on the same sample. These results were obtained thanks to the new CCD optics available at the beamline, with a pixel size of approximately 4 μm.

The images show that the crack propagates along several planes, a condition that has not been deeply investigated in a quantitative way up to now and will be the object of further investigation.

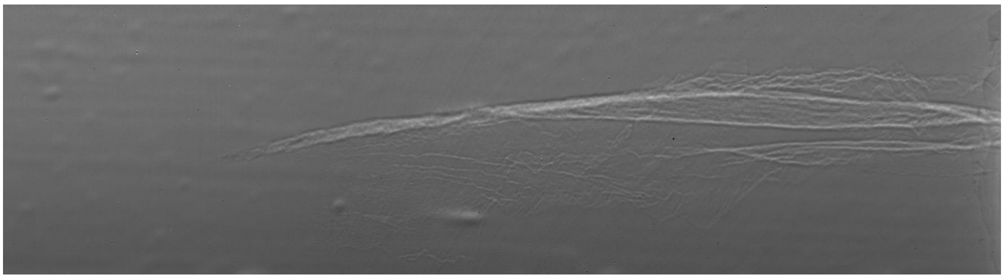

Fig. 7. PHC radiography of a long crack detected on the left side of the notch in sample 8.

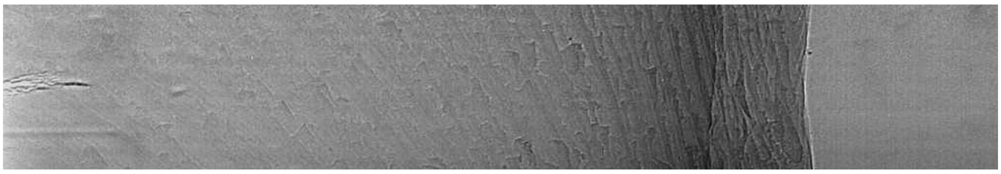

Fig. 8. PHC radiography of a short crack detected on the right side of the notch in sample 8

5. Conclusions

Preliminary results have shown that a good definition of defects position and dimension in aluminum welded joints is achievable using the imaging techniques available at SYRMEP beamline, Elettra.

Further work will regard the defects that were found in the FSW samples: in addition to the standard projections, we will produce some stereo images of the defects to evaluate their spatial localization inside the sample. The possibility of using dual-energy radiography will be also taken into consideration. We also plan to perform tomographic studies of the cracks.

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