PRELIMINARY INVESTIGATION BY SYNCHROTRON RADIATION OF CRACKS AND DEFECTS IN AA FSW SAMPLES

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ABSTRACT

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. The aim of this paper is to illustrate the preliminary results achieved in the investigation of defects in aluminum welded joints, using the phase contrast X-ray imaging techniques available at the SYRMEP beamline of the Elettra synchrotron radiation facility. Both CCD and high-resolution X-ray films were employed as detection systems.

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. A good definition of artifact defects on joints, obtained by both conventional welding techniques and Friction Stir Welding, was achieved. Successively, the investigation was restricted to joints obtained by Friction Stir Welding, which is currently the most interesting technique also from an industrial point of view. In the FSW samples prepared for the second experiment some original very small flaws were visible. The flaws size, 100 microns or more, makes them hardly detectable by means of conventional control methods. Further investigation of these small defects will provide a new unique insight on the defects that can be found in FSW samples. During the third experiment, long and a small cracks could be detected on the sides of notched samples. The images and the tomographic reconstruction 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.

1 INTRODUCTION

A very good definition of defects position and dimension in welded joints, whether obtained by conventional technology or Friction Stir Welding, is desirable from several points of view (Radaj [1], Murakami [2], Atzori [3], Hobbacher [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 on both 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 cracks, 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 the last years, some authors (Ludwig [5], Marrow [6]) have addressed the problem of short cracks nucleation and growth using X ray tomography at European Syncrhrotron Radiation Facility in Grenoble (FR). Recently, we started to investigate whether a good definition of defects position and dimension was achievable using the novel phase sensitive imaging techniques available at the SYRMEP beamline of the Elettra synchrotron radiation facility.

2 PHASE CONTRAST RADIOGRAPHY

Synchrotron radiation is electromagnetic radiation emitted by an electron beam when it is deviated by magnetic fields. Its energy spectrum covers a wide energy range, from the visible light up to hard X-rays. Its peculiar characteristics of high brilliance and coherence make it a powerful tool of investigation in different research fields. For our experiments we used the synchrotron radiation available at the SYRMEP beamline of Elettra consisting in a monochromatic X-ray beam with energy tunable between 8 keV and 35 keV.

Conventional X-ray radiography studies the X-ray 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. In this context image formation is assessed using geometrical optics. 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.

Contrary to absorption radiography, the *"phase sensitive* imaging techniques" are based on the observation of the *phase shifts* produced by the object on the incoming wave. They are described by means of wave optics.

Absorption and phase shifts are effects that occur to X-rays interacting with any kind of materials. Their relationship is considered in the definition of the material complex index of refraction n that, in the X-ray energy range, slightly differs from unity: $n = 1 - \delta + i\beta$, where δ is related to the refractive properties (i.e. X-rays phase shift) and β determines the absorption(i.e. amplitude variations).

In the energy range of 15÷25 keV, the phase shift term δ (of the order of 10^{-7}) can be up to 1000 times greater than the absorption term β (of the order of 10^{-10}), therefore it is possible to reveal phase effects even if the absorption contrast is low. The observation of the local variations in the optical path-length, determined by variations of δ, is related to Fresnel diffraction.

In general, phase information can be accessed if the X-ray source has a high spatial coherence as for synchrotron light sources (Snigirev [7]), like ESRF or Elettra. Several approaches for *phase-sensitive* radiology have been recently reported (Fitzgerald [8]). Among these, the PHase Contrast (PHC) radiography has a quite simple application: the PHC setup is the same of conventional radiography with the difference that the detector is positioned at a certain distance d from the sample.

The white beam produced in one of the Elettra bending magnets is collimated by a slit system, then it is monochromatized after passing a double-crystal Si(111) monochromator and finally it impinges the object placed at a distance of about 23m from the source. The sample-to-detector distance d can vary from 0m to about 2m. Images taken with $d = 0$ reproduce the conventional absorption radiographs. If $d > 0$ (PHC) the X-rays exiting from the samples propagate in the free space until they reach the detector. Free space propagation transforms phase modulation of transmitted beam into amplitude modulation. Contrast is originated from *interferences* among parts of the wave-fronts that have experienced different phase shifts.

According to the choice of d with respect to the size a of the feature to be identified perpendicularly to the beam direction, it is possible to discriminate between the edge detection regime ($d \ll a^2/\lambda$, where λ is the X-ray wavelength) and the holography regime ($d \approx a^2/\lambda$). In the edge detection regime images can be directly used to extract morphological information.

Furthermore, the choice of *d* depends also on the detector characteristics: *d* must be large enough to allow the small angular opening of the produced interference pattern to be converted into a length compatible with the detector spatial resolution.

The produced diffraction pattern appears superimposed to the conventional absorption radiograph on the detector and contributes mainly to enhance the visibility of the edges of the sample features.

A picture of the beamline experimental set-up is shown in Fig.1.

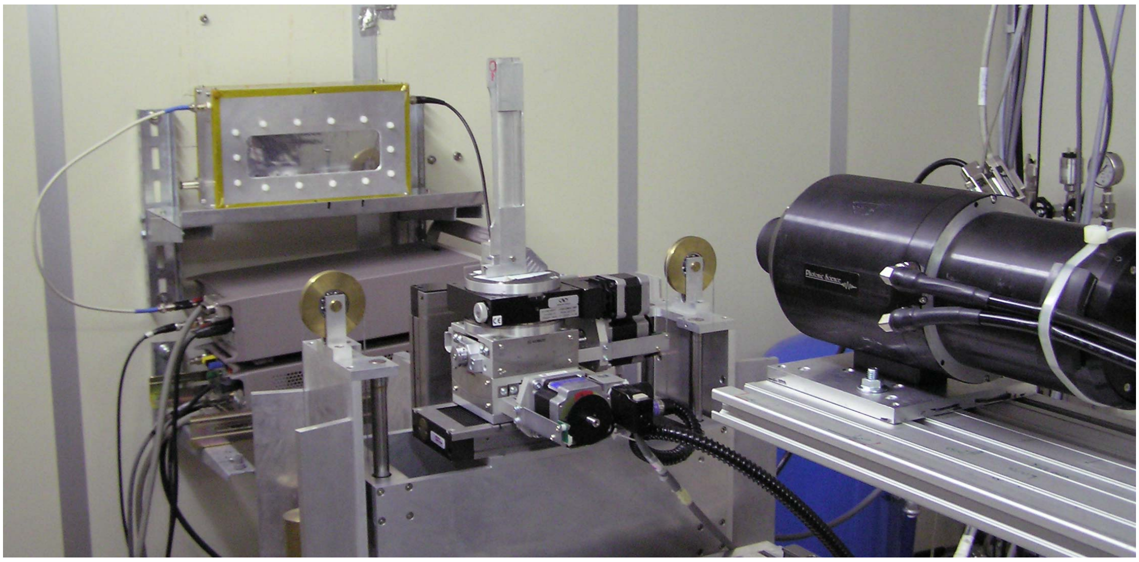

Figure 1: The experimental setup at the SYRMEP beamline in Elettra (Trieste).

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.). Samples of welded joints with artefact flaws were analyzed. The thickness *t* ranged from 5 to 10mm.

Successively, we focused on the Friction Stir Welding technique, which is currently the most interesting also from an industrial point of view. We prepared 20 6xxx FSW samples with equal dimensions (thickness 4mm, maximum area for investigation 28mm width x 100mm height,) and got PHase Contrast radiography 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 3mm, 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 encountered, the samples 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

During the first experiment, a good definition of artefact defects on aluminium joints, both conventional and FSW, was obtained by means of the PHC radiography. Both CCD detector and high-resolution X-ray films were employed as detection systems for phase contrast imaging. Some examples are given in Figg.2 and 3.

During the first experiment, the application of a different imaging technique, the Diffraction Enhanced Imaging (Chapman [10]), was also explored. The images showed the effectiveness of this technique for defects detection. Its use will be considered again in a future, when a more flexible and user-friendly experimental set-up will be available at the beamline.

Unfortunately the FSW samples prepared for the second experiment showed a mechanical resistance higher than expected, so that no small cracks were found.

Nevertheless, some original very small flaws (on the order of 100 microns or more), hardly detectable by means of conventional techniques, were visible in both the original and the stressed samples. Defects that exhibit higher absorption than aluminium are visible in sample 1 and 4, as shown in Fig. 4. 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.

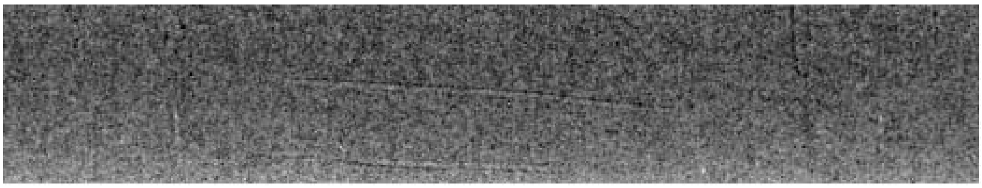

Figure 2: PHC, CCD detector: orthogonal scratches on a polished aluminium surface (t = 5mm).

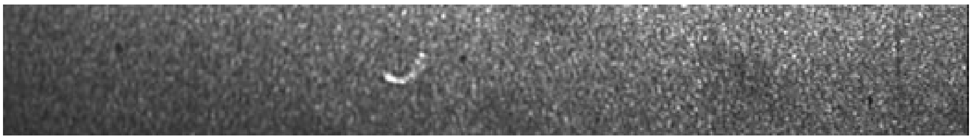

Figure 3: PHC, high-resolution X-ray film: an inclusion inside a FSW sample (t = 5mm).

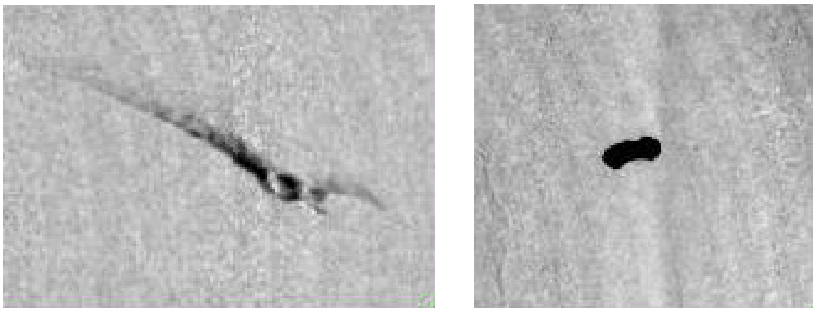

Figure 4: PHC radiographies of sample S1, CCD detector, standard optics: flaws with higher absorption than aluminium. Approx. flaws extension is about 1.5 mm (left) and 0.35 mm (right).

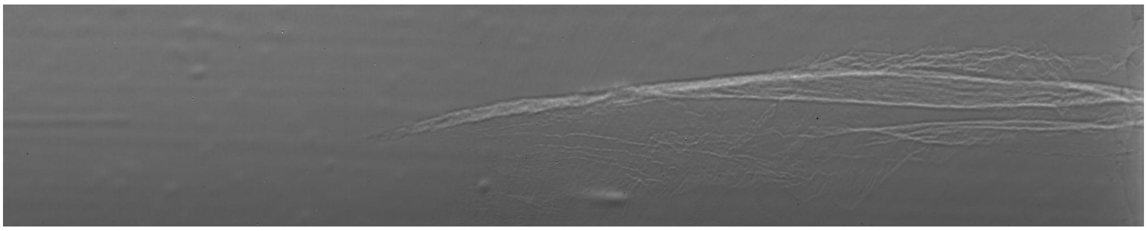

Figure 5: PHC radiography of a long crack detected on the left side of the notch in sample 8. Detector was CCD equipped with high-resolution optics. The crack maximum extention is about 3.5 mm.

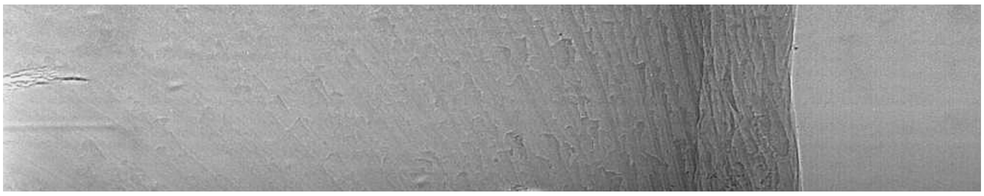

Figure 6: PHC radiography of a short crack detected on the right side of the notch in sample 8. Detector was CCD equipped with high-resolution optics. The crack extension is about 0.7 mm.

The most interesting preliminary results of the last experiment are also shown. In Figg. 5 and 6 respectively, a long and a small crack could be detected on the two sides of the notch on the same sample, previously subjected to axial loading. Fig. 7 shows two tomographic slices of a notched sample that had previously been subjected to combined torsion and bending. The 3D reconstruction of the zone of interest in the same sample is shown in Fig. 8. These results were obtained thanks to the new CCD optics available at the beamline that allows a pixel size reduction from 14µm to approximately 4µm.

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.

5 CONCLUSIONS

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

Further work will regard the defects that are found in AA and AA FSW samples: in addition to the standard projections, we will produce some stereo images and tomographic quantitative studies of the defects. The possibility of using dual-energy radiography will be also taken into consideration.

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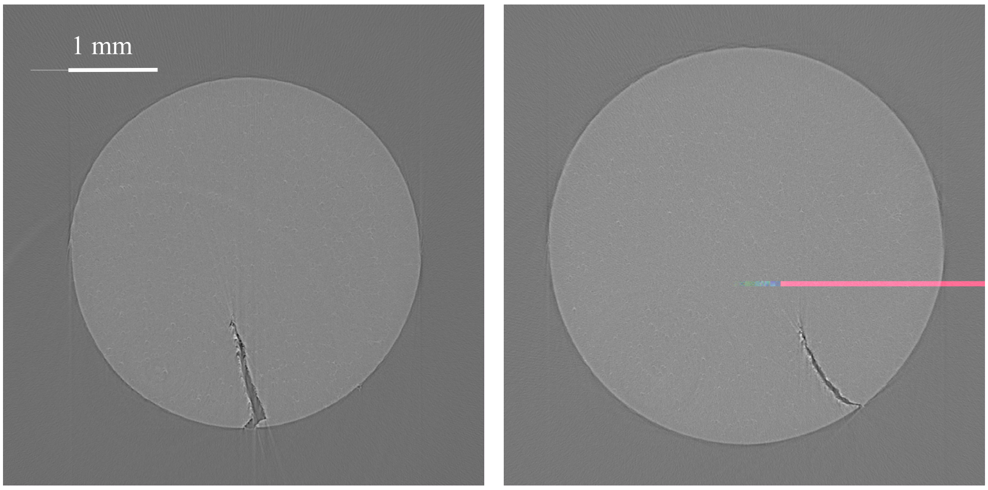

Figure 7: PHC, two tomographic slices (distance 4 µm) of a crack in sample P8. Detector was CCD equipped with high-resolution optics. The crack extension is about 1.24 mm.

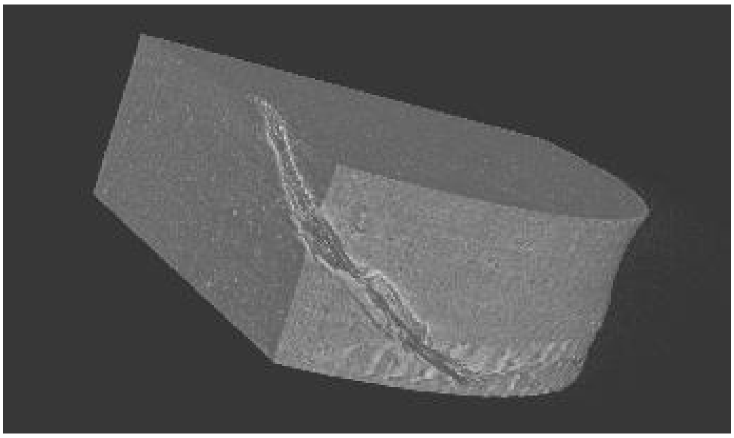

Figure 8: PHC, 3D reconstruction of a crack in sample P8 (*t* = 4mm). Detector was CCD equipped with high-resolution optics. The crack extension is about 1.24 mm