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Three-dimensional local residual stress and orientation gradients near graphite nodules in ductile cast iron

Y.B. Zhang [a,*], T. Andriollo [b], S. Fæster [a], W. Liu [c], J. Hattel [b], R.I. Barabash [d]

[a] Section for Materials Science and Advanced Characterization, Department of Wind Energy, Technical University of Denmark, Risø Campus, Roskilde, DK-4000, Denmark
[b] Department of Mechanical Engineering, Technical University of Denmark, DK-2800, Kgs. Lyngby, Denmark
[c] Advanced Photon Source, Argonne National Laboratory, Argonne, IL, 60439-4800, USA
[d] Materials Science & Technology Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN, 37831-6118, USA

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ABSTRACT

A synchrotron technique, differential aperture X-ray microscopy (DAXM), has been applied to characterize the microstructure and analyze the local mesoscale residual elastic strain fields around graphite nodules embedded in ferrite matrix grains in ductile cast iron. Compressive residual elastic strains are measured with a maximum strain of ~6.5–8 × 10^{-4} near the graphite nodules extending into the matrix about 20 μm, where the elastic strain is near zero. The experimental data are compared with a strain gradient calculated by a finite element model, and good accord has been found but with a significant overprediction of the maximum strain. This is discussed in terms of stress relaxation during cooling or during storage by plastic deformation of the nodule, the matrix or both. Relaxation by plastic deformation of the ferrite is demonstrated by the formation of low energy dislocation cell structure also quantified by the DAXM technique.

1. Introduction

Ductile cast iron (DCI) is an attractive engineering material, as it has strength and toughness very similar to steel, and the machinability advantages make it very cost effective [1]. An example of industrial applications is the heavy components for wind turbine, e.g. the main shaft. One design requirement for such components is good fatigue resistance, as the fatigue failure is a main failure mode during their service life [2].

From a microscopic point of view, DCI is a composite material, consisting of graphite nodules embedded in a metal matrix which, in most engineering applications, can be either ferrite, or pearlite or a mixture of the two [1]. The differences in the thermal expansion coefficients between the metal matrix and the graphite nodules can lead to local thermal residual stresses in the composites during cooling from the processing temperature to room temperature [3,4]. Due to the presence of the local residual elastic stresses, fatigue cracks may be initiated at the nodules because of overstrain, as the local residual stresses may be larger than the flow stress of the metal matrix. But they may also be lower as they may relax by plastic deformation of the nodules or the surrounding volume [5]. In the past many studies have been conducted to quantify and model the residual stresses in metal matrix composites containing particles that are harder than the metal matrix, e.g. SiC or Al_2O_3 reinforced aluminum matrix composite [6,7] and Al/W metal matrix composite [8]. For a system like DCI, where the particles (graphite nodules) are considerably softer than the metal matrix, there has however not been much knowledge about the local residual stress. Many researchers believed the local residual stresses to be minor, considering the fact that graphite is soft; and the local residual stresses were neglected in most micromechanical models [9]. However, recently the formation of residual stress comparable to the material yield stress has been predicted by finite element models in DCI [10]. To optimize design and processing of DCI components, the magnitude of the local mesoscale residual stresses must therefore be known.

It is however a challenging task to quantify local residual stresses experimentally. Recently, the development of new experimental characterization techniques has given promising possibilities. For example, a novel synchrotron X-ray technique, the so-

* Corresponding author.
E-mail address: yubz@dtu.dk (Y.B. Zhang).

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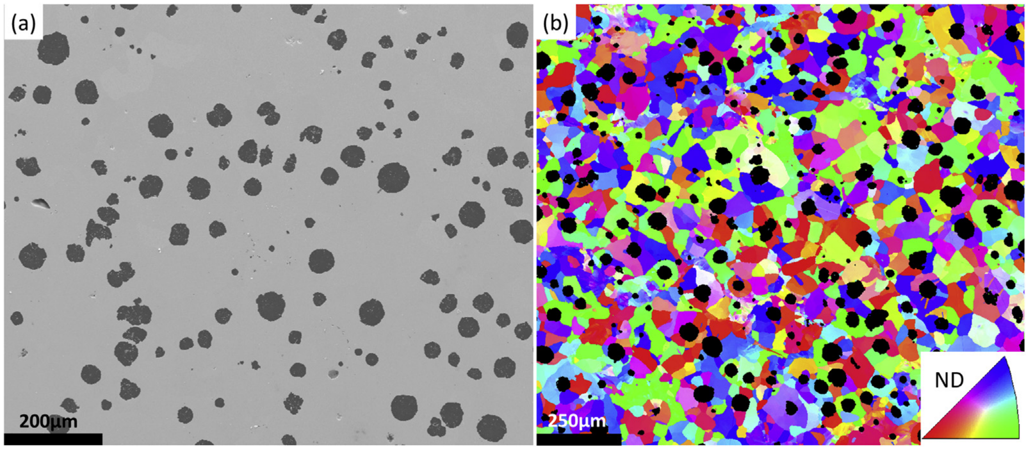

Fig. 1. Microstructures of the DCI showing the graphite nodules and metal matrix. (a) Scanning electron microcopy image and (b) EBSD map. In (a) dark regions are graphite nodules and the rest is metal matrix, while in (b) the black particles are graphite nodules and the colored grains are the metal matrix. The colors of the matrix grains correspond to the crystallographic orientation along the specimen surface normal direction (ND) (see the insert).

Table 1
Chemical composition of the sample (mass%).

C	Si	Mn	P	S	Cr	Ni	Co	Cu	Ti	V	Mg	Ce	Se
3.68	2.30	0.22	0.015	0.011	0.027	0.048	0.024	0.016	0.017	0.014	0.11	0.042	0.043

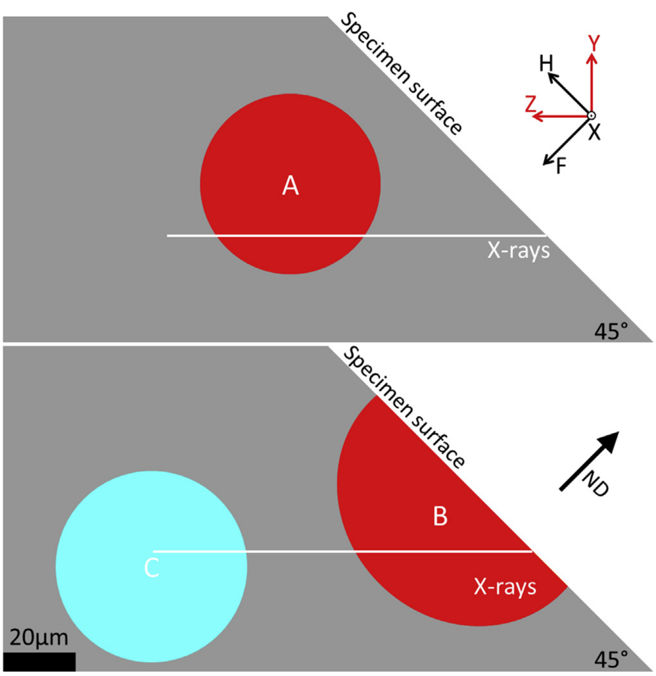

Fig. 2. Sketches showing a side view of the detailed scanning positions relative to the selected nodules. The selected nodules are marked by A, B and C. Specimen surface normal direction (ND) is marked by the black arrow. The white lines represent the projections of the mapping planes illuminated by the incoming X-rays, which are along the Z direction.

called differential aperture X-ray microscopy (DAXM), has been developed during the last 15–20 years for non-destructive 3D characterization of microstructure and local elastic strains [11,12]. With DAXM, local elastic strain distribution inside individual grains has been measured in e.g. deformed bicrystal Ni [13] and NiAl-Cr(Mo) composite [14]. The use of focused microbeam offers spatial resolutions of sub-micrometers [15].

Table 2
Sizes and positions of the selected three nodules.

Graphite nodule	Diameter (µm)	Depth (µm)[a]
A	50	40
B	72	10
C	63	78

[a] Depth means the perpendicular distance from the center-of-mass of the nodules to the sample surface.

In this study, we use DAXM to characterize the microstructures and local residual strains/stresses in matrix grains surrounding graphite nodules in a DCI sample. The objective of the study is to answer the following questions: i) are the matrix grains plastically deformed? ii) what is the magnitude of the residual elastic stress and is it comparable with the flow stresses of the cast iron? iii) how the residual elastic stress distributes? and iv) how residual stress relaxes? A DCI sample is chosen based on a previous study, where the fatigue properties of the sample are already available in a large data base. The results on the local residual stresses will provide a new aspect to evaluate the obtained fatigue properties.

2. Material and methods

2.1. Materials

Metal mold DCI was chosen for the study. A specimen was extracted from the head of a sample that has been fatigue tested to failure after ~5 million cycles under stress level 5.5 as described in Ref. [16]. It therefore was considered as not affected by the fatigue test. The sample consists of almost spherical graphite nodules and a metal matrix with a relatively homogeneous structure, being mainly ferrite with a small fraction of perlite (~5%). The graphite nodules were distributed relatively homogeneously in the metal matrix (see Fig. 1a). The mean size (equivalent circle diameter) and volume fraction of the graphite nodules were ~30 µm and 11.5%, respectively. The mean distance between nodules and the