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Uncovering the local inelastic interactions during manufacture of ductile cast iron: How the substructure of the graphite particles can induce residual stress concentrations in the matrix

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ABSTRACT

Recent X-ray diffraction (XRD) measurements have revealed that plastic deformation and a residual elastic strain field can be present around the graphite particles in ductile cast iron after manufacturing, probably due to some local mismatch in thermal contraction. However, as only one component of the elastic strain tensor could be obtained from the XRD data, the shape and magnitude of the associated residual stress field have remained unknown. To compensate for this and to provide theoretical insight into this unexplored topic, a combined experimental-numerical approach is presented in this paper. First, a material equivalent to the ductile cast iron matrix is manufactured and subjected to dilatometric and high-temperature tensile tests. Subsequently, a two-scale hierarchical top-down model is devised, calibrated on the basis of the collected data and used to simulate the interaction between the graphite particles and the matrix during manufacturing of the industrial part considered in the XRD study. The model indicates that, besides the viscoplastic deformation of the matrix, the effect of the inelastic deformation of the graphite has to be considered to explain the magnitude of the XRD strain. Moreover, the model shows that the large elastic strain perturbations recorded with XRD close to the graphite–matrix interface are not artifacts due to e.g. sharp gradients in chemical composition, but correspond to residual stress concentrations induced by the conical sectors forming the internal structure of the graphite particles. In contrast to common belief, these results thus suggest that ductile cast iron parts cannot be considered, in general, as stress-free at the microstructural scale.

1. Introduction

The discovery of ductile cast iron, also referred to as nodular cast iron or spheroidal graphite iron (SGI), dates back to 1943, when Keith D. Millis of the International Nickel Company Research Laboratory found out that a small addition of

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magnesium to gray cast iron resulted in the formation of spherical graphite particles (Loper Jr., 1994). In the subsequent decades, the material has experienced an enormous and constantly growing development (Labrecque and Gagne, 1998), certified by the fact that today, more than 70 years after its introduction, it represents as much as 25% of the total castings produced worldwide (47th Census of World Casting Production, 2013). The main reason behind this phenomenal success is the unique combination of castability, high ductility and strength this material can offer, along with lower prices compared to traditional low carbon steels (Ductile Iron Society, 2013). This makes SGI the best choice for manufacturing small and medium sized heavily loaded parts with high demands for consistent quality for the automotive industry and very large industrial components with extreme demands for mechanical properties, particularly fatigue strength and fracture toughness (Tiedje, 2010).

Due to the primary technological importance that SGI has in our society, and the huge monetary losses associated with premature failure of critical SGI components in the automotive and energy sectors, major efforts have been devoted in the past years to understand the fracture mechanisms under both monotonic and cyclic loading, as reported in a recent review article (Hütter et al., 2015a). In this respect, a major challenge is represented by the material microstructure, which, in contrast to many other metallic alloys, is not homogeneous but consists of spherical graphite particles, called spheroids or nodules, embedded in a metallic matrix which can be either ferritic, pearlitic or a mixture of the two (Grimvall, 1997; Sjögren and Svensson, 2004). The impact of this composite nature at the micro-scale on the material fracture behavior has been documented by fracture tests conducted on ferritic and ferritic-pearlitic SGI, which have clearly shown that the crack propagation path is strongly affected by the presence of the graphite nodules (Baer, 2014; Di Cocco et al., 2014; Fernandino and Boeri, 2015; Iacoviello and Di Cocco, 2016). The consequence is that the fracture process of SGI can hardly be explained on the basis of standard theoretical models which consider the material as homogeneous (Dong et al., 1997; Berdin et al., 2001). Prompted by the recent progress in advanced characterization techniques such as micro X-ray tomography, which allows unprecedented insight into the morphology and distribution of the microstructural phases, more advanced models which take into account the local interactions arising between the different microstructural elements are now emerging, whose development is a current research area (Costa et al., 2010; Collini and Pirondi, 2014; Hütter et al., 2015b; Salomonsson and Olofsson, 2017; Fernandino et al., 2017).

Concerning this last point, recent research by the present authors has shown that, despite most of the models proposed so far consider SGI as stress-free at the microstructural scale, significant interactions between the graphite nodules and the matrix occur during the manufacturing process, leading to a localized residual stress state in the material. The reason is the larger thermal contraction experienced by the matrix during solid-state cooling compared to the nodules, with the former that tends to compress the latter in a hydrostatic fashion. This aspect was often neglected in the past, probably due to the scarce knowledge of the mechanical properties of the nodules, pointed out in Andriollo and Hattel (2016), and the technical difficulties of performing direct residual stress measurement around embedded particles whose diameter does not normally exceed 150 µm. In the last 10–15 years however, such experimental limitations have been progressively disappearing due to the advent of new, powerful X-ray diffraction techniques based on synchrotron radiation, which have dramatically increased the possibilities of characterizing the material stress state at the micro-scale (Yang et al., 2002, 2004). Indeed, by exploiting one of these new techniques, known as differential-aperture X-ray microscopy (DAXM), the existence of a non-negligible residual elastic strain field in the ferrite matrix region surrounding the nodules has recently been shown for the first time in a thin sample extracted from an industrial SGI component (Zhang et al., 2016). In this respect, it is worth remarking that the reduced size of the sample and the sub-surface location of the nodules selected for the measurements have allowed ruling out the hypothesis that the recorded elastic strain field could be associated to either a macroscopic residual stress field or to surface-related effects. Moreover, the gradient of the recorded elastic strain has been found globally consistent with that expected on the basis of the type of thermo-mechanical interaction between the nodules and the matrix described above. Altogether, these results are an indicator that the stress-free assumption may be inadequate to describe the room-temperature microstructure of SGI.

Unfortunately, despite showing unambiguously that the nodules and the matrix interact mechanically during manufacturing, the findings of Zhang et al. (2016) do not provide a complete picture of the residual elastic strain field existing around the nodules, nor of the associated residual stress field, which would be essential for developing any advanced SGI fracture theory. The reason is twofold and can be better appreciated with the help of Fig. 1. First of all, only one component of the elastic strain tensor, corresponding to the normal strain ε_{FF}^{el} along the F-axis of the F–H coordinate system of Fig. 1(a), was measured, which is not sufficient to derive the full stress tensor via the generalized Hooke's law. Secondly, the variation of this single strain component was recorded along straight parallel paths, depicted with blue dots in Fig. 1(b), whose non-radial orientation complicates significantly the interpretation of the results. To compensate for these issues, one possibility is to construct a theoretical model which simulates the relevant physics and allows predicting both the full residual elastic strain and stress fields around the nodules. If the model is capable of reproducing the experimentally recorded elastic strain within engineering accuracy, the linearity of Hooke's law should guarantee that the model can be used to estimate the stress with a similar level of accuracy.

A first, partial attempt to apply the strategy just described to estimate the residual stress field around the graphite particles was made in Zhang et al. (2016), on the basis of the linear elastic micro-mechanical unit cell model proposed in Andriollo et al. (2016b) to simulate the thermo-elastic properties of ferritic SGI at room temperature. Despite being able to explain the global tendency of ε_{FF}^{el} to become less compressive with increasing values of the z-coordinate (see Fig. 1), the analysis based on this simplified model was affected by deficiencies so severe that it could not be used to make any