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# USE OF HIGH INTENSITY X-RAY ANALYSIS AS TOOL TO CREATE NEW, FUNDAMENTAL MODELS FOR PHASE TRANSFORMATIONS AND RESIDUAL STRESS IN DUCTILE CAST IRON

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## 1. introduction

Cast irons have been used for engineering purposes for thousands of years, and still, today they are essential our society. Their mechanical properties are primarily determined by the shape, size and distribution of graphite in the steel matrix. [1]

The mechanisms behind graphite growth and development of shape and their coupling to raw material quality and process conditions remain unknown.[2] Also the mechanisms leading to the formation of residual stresses are also not fully clear.[3;4]

Extensive experimental data has been produced and utilized to generate empirical correlations via statistical methods, showing that e.g. the shape and distribution of graphite affect ductility, yield strength and fatigue properties while carbides influence strength and wear properties.[1] However, little is known on why such correlations hold true, as the individual mechanisms which control the material behavior at the micro-scale have not been clarified.

Recent advances in high resolution X-Ray methods that involve use of synchrotron facilities have made it possible to do high resolution, in-situ experimental studies of phase transformations in engineering materials thus providing detailed and accurate information on the processes that take place during such phase transformations.[5;6]

This paper describes how such facilities can be applied to study solidification of cast iron and formation of residual stress after eutectoid transformation by resolving the processes in 3D and time.

## 2. 3D studies of solidification and microstructure in ductile cast iron

Solidification was studied in an environmental cell where the sample could be melted and solidified while 3D X-Ray recordings were made as described in.[6] During solidification 62 tomograms consisting of each 360 2D projections were acquired so that in selected sub-volumes it is possible to study in detail formation and growth of nodules. Fig. 1 shows 3 such sub-volumes extracted from the total sample volume. It is possible to follow how the size and shape of individual nodules develop depending during solidification.

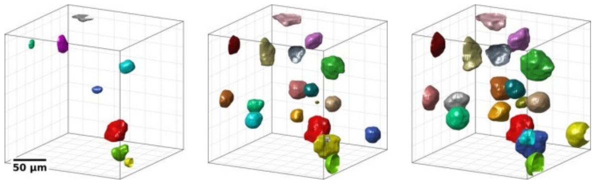


***Fig. 1. Tomography images from a sub-volume. Images are taken 360, 400 and 480s into the recording. Images show formation of nodules revealing how some nodules remain spherical while others change shape.***

The recordings allow detailed quantitative studies of spheroidal graphite growth and direct comparison to model predictions highlighting how and where models for growth need to be improved. We can show the effect of the local arrangement of graphite, liquid and austenite on the individual graphite nodule growth patterns and while studies of large ensembles illuminates both the average and the extreme nodule growth behavior. At the same time, we can study the development graphite size distribution with time (see figure 2) and of particle shapes during the course of solidification providing new and unexpected insights and addressing unresolved issues regarding the development of particle morphologies.

## 3. Experimental and numerical analysis of graphite-matrix interaction

It is well known that ductile iron parts, depending on their size, may contain residual stresses developing over distances of a few millimeters or more, which arise due to the presence of constraints that hinder the free thermal contraction of the material during cooling.

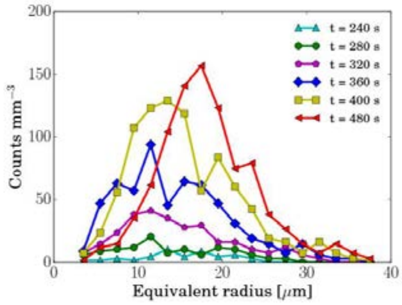


***Fig. 2.*** ***Nodule size distribution measured in a sub-volume as function of time.***

The intrinsic composite nature of ductile iron suggests the possible formation of another type of residual stresses, at much shorter length scales, associated with the thermal contraction mismatch between the two main metallurgical phases forming the material microstructure: the graphite nodules and the metallic matrix.[5] Surprisingly, the subject has not received much consideration in the past, probably due the common belief that the graphite particles are very soft and unable to withstand any kind of loading. However, experimental evidence exists for their mechanical importance, especially at relatively high temperature and under compressive loadings, indicating that ductile iron might not be considered as a merely "voided material" in all situations, as it is illustrated in figure 3a and 3b.

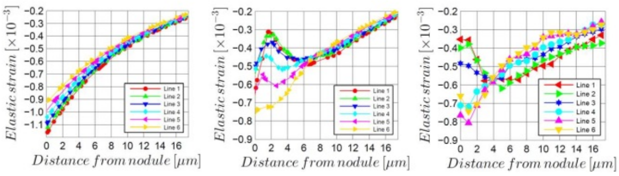


***Fig. 3.*** ***Residual elastic strain around a graphite nodule assuming that: a) the nodule has no internal microstructure, b) that its internal structure consists of several conical sectors, c) local stress measured with synchrotron X-Ray diffraction***

To investigate the existence of residual stresses at the microscale level, the elastic strain in the ferrite matrix surrounding a few nodules lying beneath the surface of a thin sample was measured using a novel 3D X-ray diffraction technique.[5] The measurements revealed that local stresses up to approximately half the macroscopic yield strength of ductile iron may remain in the microstructure after manufacturing. It was also shown that local residual stress varies with orientation relative to crystallographic sectors in the graphite nodule, as shown in fig. 3c.

As a consequence, a theoretical model was developed where the internal subdivision of the nodule into conical sectors was reproduced in detail.[7] In addition, numerical simulations allowed clarifying that the conical sectors making up the nodules create residual stress concentrations in the matrix, which correspond to the elastic strain fluctuations seen in Fig. 3b when the distance from the nodule is less than ≈ 5-6 microns. New studies are being carried out to investigate the impact of this complex residual stress field on the micro-scale deformation of ductile iron upon loading. Fig. 4 shows an example of calculated plastic strain in a ductile iron volume subjected to mechanical load. Colors show local variation in plastic strain based on the distribution of nodules.

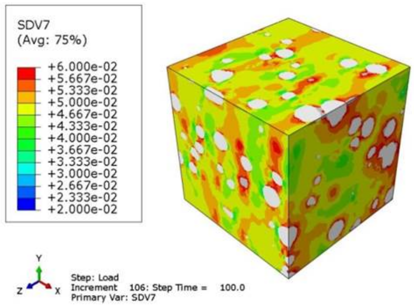


***Fig. 4.*** ***Calculated local plastic strain around graphite nodules in a volume of ductile cast iron.***

## 4. Conclusion

With the increased use of synchrotron X-rays for in situ experiments on casting-related phenomena we can expect a large improvement in our understanding which provides a much firmer basis for models and predictions of microstructure formation. This paves the way for higher degree of tailoring of processes and alloys for specific purposes and requirements as well as general improved performance of cast components.

## 5. References


[1] D.M. Stefanescu, ed. (2017), Cast Iron Science and Technology ASM International.

[2] J. Lacaze, N. Valle and K. Theuwissen, (2013), Redistribution and Effect of Various Elements on the Morphology of Primary Graphite in Cast Iron, Advances in Materials Science and Engineering

[3] T. Andriollo, N. Vedel-Smith, J. Thorborg and J. H. Hattel, Internal casting stresses and dimensional stability. In Cast Iron Science and Technology (Edited by D. M. Stefanescu), Chap. 4.11. ASM International, (2017).

[4] N. K. Vedel-Smith, J. Rasmussen and N. S. Tiedje, (2015), Thermal Distortion of Disc-Shaped Ductile Iron Castings in Vertically Parted Moulds, Journal of Materials Processing Technology 217, pp. 262-271

[5] Y. Zhang, T. Andriollo, S. Fæster, W. Liu, J. H. Hattel and R. I. Barabash, (2016), Three-dimensional local residual stress and orientation gradients near graphite nodules in ductile cast iron, Acta Mater. 121, pp. 173-180

[6] M. K. Bjerre, M. Azeem, R. C. Atwood, N. S. Tiedje and P. D. Lee, (2018), Synchrotron quantification of graphite nodule evolution during the solidification of cast iron, Acta Mater. Accepted for publication.

[7] T. Andriollo, K. Hellström, M. R. Sonne, J. Thorborg, N. S. Tiedje and J. H. Hattel, (2018), 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, J. Mech. Phys Solids, Volume 111, pp. 333-357