Impact of local Si segregation on strain localization in ductile cast iron

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Abstract. The distribution of Si content in tensile deformed ductile cast iron has been characterized using electron microscopy and correlated to the strain distribution determined based on 3D tomography data collected before and after tensile deformation and digital volume correlation analysis. The results show that the high plastic strain regions localize in bands consisting of large graphite nodules and deformed matrix with high Si content connecting the graphite nodules in the first-to-solidify regions. The bands are aligned about 45° with respect to the loading direction, which is close to the maximum shear direction.

1. Introduction

Ductile cast iron (DCI), due to its high performances and versatility at relatively low cost compared to steels with analogous performances, is widely used in different applications such as small and medium sized heavily loaded part for the automotive industry, e.g. gears and brakes, and very large industrial components with extreme demands for mechanical properties e.g. wind turbine hub [1]. DCI consists of very soft graphite nodules and steel matrix which have quite different mechanical properties. Analogous to other types of cast irons, is based on the Fe-C-Si system and contains some alloy elements intentionally added to enhance one or more useful properties. With increasing Si content, the thermodynamic activity of C in the liquid can be increased, promoting stable eutectics and inhibiting the formation of cementite. At the same time, Si can lower the carbon content of the eutectic promoting the formation of graphite nodules during solidification. Additionally, Si dissolves in the steel matrix, providing solid solution strengthening. However, Si segregates upon solidification leading to a heterogeneous chemical distribution in the steel matrix, which can lead to local strength difference, being higher at Si rich regions and lower at Si rare regions [2]. Lekakh et al. [3] has shown that such segregation plays an important role on the mechanical properties of ductile cast iron. Fernandino et al. [4] developed 2D multi-scale model for capturing how the damage proceeds in an inhomogeneous microstructure at microscale. He also reported that cracks preferentially initiated at the nodule-matrix interface and propagated across internodular ligaments avoiding the low-Si last-to-solidify (LTS) zones [5]. However, it is worth pointing out that both the materials and the mechanical behaviour are in 3D, which implies that the heterogeneities on the subsurface could affect the mechanical reactions on the sample surfaces. Therefore, a more accurate analysis of the correlation of local strain to inhomogeneous microstructure in 3D is desirable.
In a recent study, we have developed a new 3D method to correlate the local strain localization to the microstructural heterogeneities [6]. First we use 3D X-ray tomography to follow in situ the 3D microstructural evolution during tensile deformation, to determine the 3D strain distribution using a digital volume correlation (DVC) method [7]. Then the microstructure on a 2D section inside the 3D volume is characterized using optical microscopy for analysing the strain partitioning. Although the correlation is conducted on a 2D section, the analysis is representative for true 3D behaviour. In the present paper, we use the same method to study the strain partitioning with respect to the Si segregation, measured using energy dispersive X-ray spectroscopy (EDX) in a scanning electron microscope.

2. Experiments
A miniaturized dog-bone shaped tensile specimen with a gauge length of 10 mm and a cross-section of 1 x 2 mm² was extracted from a large DCI casting. The main alloy elements beside Fe were C (3.68 wt%), Si (2.3 wt%), Mn (0.22 wt%), Mg (0.11 wt%). It consists of almost spherical graphite nodules homogeneously embedded in a metal matrix being mainly ferrite with a small fraction of pearlite about 5%. The volume fraction and average size of the graphite nodules are 11.5% and 30 µm respectively. The specimen was mounted on a tensile test rig attached inside a Zeiss Xradia 520 Versa microscope and loaded in tension to a macroscopic strain of ≈ 10%. Before and after the tensile load, the specimen was scanned with X-ray computed tomography to monitor the microstructure evolution in 3D. Subsequently, DVC was employed to calculate the microscopic strain field attendant with the mechanical deformation with a spatial resolution of 60×60×60 µm³. Based on this, the strain value calculated from the 3D volume was obtained via linear interpolation. For microstructural characterization of the tensile deformed specimen, a 2D section (≈120 µm from one lateral surface) of the 3D volume was ground and polished, followed by SEM and EDX characterization with dwell time of 1 s and 128 frames.

3. Microstructures characterized using SEM
The SEM images showing the microstructure after the tensile test on the polished surface are presented in figure 1, where graphite nodules and matrix grains can be distinguished. Within graphite nodules some internal structures, e.g. conical sector structure and steel particles are seen, which are typical for DCI [8]. The interfaces between the graphite nodules and surrounding matrix debond upon tensile deformation at the two opposite sides that are perpendicular to the loading direction. The spherical white region marked by an arrow in figure 1 is believed to be a graphite nodule that fell out during polishing. Only in a few cases, cracks are observed inside the graphite nodules.

This result in that the fracture mechanism is mainly nodule-matrix debonding differs from previous observations on the 2D sample surface [9, 10], suggesting that the results seen at the sample surface might not be representative of bulk behaviours. Iacoviello [11] and Di Cocco [10] have confirmed that the stress state around the nodules is linked to the role of graphite nodules and thus the damaging mechanisms. As the microscopic stress state on the specimen surface differs from that in the bulk, different damaging mechanisms can be active. Furthermore, Zhang [12] has demonstrated that the residual stress around the bulk nodules differs from that around the nodules exposed to the sample surface. It is worth pointing out that the characterized section is in the bulk while the sample was loaded and only exposed by removing a layer (≈120 µm) away, which might be the reason for more pure graphite-matrix debonding in the present study.

Figure 1. SEM image showing the debonding damage mechanism, and the inset presenting the nodule in high magnification.
Additionally, the finding that only a few of cracks are observed in the graphite nodules is somewhat different from previous results [9, 13, 14]. A model with a 3D periodic cubic unit cell with a spherical nodule in the centre and a 2D square periodic unit cell with a circular central nodule subjected to plane-stress conditions were developed. These two models are supposed to represent the material behaviour in the bulk and on the specimen surface respectively. The model details can be found in [15]. The simulation results are shown in figure 2. The black curves represent the shape of undeformed nodules, while the blue and red solid curves are the shapes of deformed nodules in the bulk and on the sample surfaces respectively. R, X and Y are the radius of the undeformed nodules, length along and perpendicular to the loading direction. This figure is quite revealing and shows that the nodules on the surfaces become flatter than the nodules in the bulk, which means that the metal matrix compresses the nodules more and thus more cracks are likely to form in the nodules on the sample surfaces. Therefore, it is not particularly surprising to observe fewer cracks in the nodules in the present study, given the fact that the investigated section is in the bulk.

4. Si segregation

4.1. Si distribution
Si has a negative segregation during solidification of cast irons, which means that the Si preferentially concentrates in the austenite, leaving a lower Si content in the liquid melt during solidification. Consequently, the first-to-solidify (FTS) zones contain a higher Si content, while the LTS zones have the lowest Si content. Figure 3(a) shows the Si distribution map measured after the tensile test. In the map, the dark blue areas containing Si content lower than 0.5 wt% are graphite nodules and the yellow areas with Si content higher than 2.5 wt% are considered as the FTS zones. The areas with a relatively low Si concentration which are displayed in light blue surrounded by thin green areas are treated as the LTS zones.

![Figure 3](image)  
Figure 3. (a) Si concentration map, (b) strain distribution and (c) the correlation between them. Region A and B in (c) marked the high strained regions with low and high Si concentration respectively.

It can be noticed that a considerable amount of small nodules with size less than 25 µm are located mainly in the LTS zones, while almost all large nodules with size in the range 25 - 75 µm are within the FTS zones. The large nodules nucleate at the beginning of the solidification and thus have long time to
grow than the rest small nodules. It also indicates that the material solidifies in the very beginning with large nodules surrounded by austenite.

4.2. Strain distribution
It is well acknowledged that localized deformation generally develops within a broad range of ductile materials, which lead to intense deformation and final fracture. The von Mises equivalent strain obtained from DVC calculation is shown in figure 3(b). Yellow bands with strain values higher than 0.15 showing the strain localization are seen, which are oriented at approximately 45° with respect to the loading direction. Low-strain areas can be seen in areas between these bands. It, therefore, can be inferred that there are local softening regions in the tested materials, which allow the formation of localized strain bands.

4.3. Correlation of local strain to Si segregation
With the purpose of directly visualizing the role played by the local Si concentration on the mechanical behavior in microscale, the local strain values upon loading is plotted in figure 3(c), where the horizontal and vertical axes represent the Si content and strain values respectively. Noticeably, the Si content of voxels with strain values higher than 0.15 are mainly located in regions marked as A and B. By re-examining the Si distribution in figure 3(a), it can be seen that region A and B represent the strain of the graphite nodules and the FTS zones respectively. Furthermore, it is noticeable that the local strain in the LTS zones with Si concentration of 1.5 wt% to 2.1 wt% is lower than 0.15. This results clearly shows that the FTS zones tend to deform more plastically and thus with higher strain values compared with the LTS zones showing relatively lower strain values. Previous study shows that the matrix in FTS and LTS zones are mainly ferrite and pearlite respectively. The difference in local deformation behaviour of FTS and LTS zones thus might stem from two factors: the different mechanical properties between ferrite and pearlite or the effects of graphite nodules. On one hand, as well-acknowledged, the amount of carbon in ferrite is approximately 0.006% at room temperature since carbon atoms are larger than the lattice interstitial voids of ferrite by a factor of two. Ferrite is thus characterized by good ductility but relatively low hardness and strength, which is quite analogous to the mechanical properties of pure iron. Nevertheless, the structural components of pearlite are not only soft ferrite but also high-hardness cementite layers, which strengthen the pearlite. Consequently, the ferrite tends to be deformed more and easier than pearlite upon loading, and thus has higher strain values. On the other hand, the graphite nodules are soft and can lead to stress concentration around nodules.

However, it should be also noticed that most of voxels in FTS zones with high Si content shows low strain values. With the aim to clarify which voxels in the FTS zones and in the nodules are highly strained, the voxels in region A and B in figure 3(c) are extracted from the Si map, as shown in figure 4(a) and (b) respectively. As can be seen evidently, the voxels with high strain values both in the FTS zones and in the nodules are from the same bands, which are oriented at certain angles with respect to the loading direction.

Another striking observation to emerge from figure 3(c) is that although both nodules and FTS zones have some voxels with high strain values, the nodules have more voxels with strain values larger than 0.18. The finding indicates that the graphite nodules can be considered as a much softer phase than ferrite even though they cannot be treated as voids, which means the main load carrying area decreases. Therefore, it is expected that the matrix adjacent to the graphite nodules, ferrite, would have higher stresses and thus higher strain values compared with the pearlite mainly being located in the LTS zones. Furthermore, it can be clearly identified that the deformation bands are mainly located in areas of lines of graphite nodules, which is in good agreement with Fernandino’s investigation that fracture occurs across internodular ligaments [5]. Much more ferrite and nodules along nodule lines as seen in figure 3(a) causing higher stress between nodules might make for the higher strains in bands.
5. Conclusions
The Si distribution and strain localization in tensile deformed DCI have been characterized using EDX, computed tomography and DVC. Possible correlation between them has been investigated. The results show that the high plastic strain regions localize in bands aligned about 45° with respect to the loading direction, which is close to the maximum shear direction. The bands mainly consist of large nodules and connected deformed matrix with high Si concentration from FTS regions.

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