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Hole Drilling Residual Stress Evaluations in Cast Iron

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Abstract. Incremental hole drilling for residual stress measurement are widely used in industry today and is considered to be a cheap and fairly reliable method for stress measurements. Even though the method assumes isotropic material, it has been expanded to orthotropic materials such as composite laminates. With heterogeneous material like grey cast iron, the reliability and accuracy of the method still often fails to provide residual stress data valid for analysis. Cast iron microstructural aspects that complicate the analysis are the graphite and its morphology, variations in matrix structures and casting defects. These features can extend over different length scales and give cast iron highly localised mechanical properties. Global engineering parameters, such as Young's modulus and Poisson's ratio, are used together with the locally measured strains to calculate the residual stresses. Utilizing global material parameters while measuring locally can provide false stress results. Grey cast iron exhibits a non-linear elastic behaviour and the Young's modulus can change significantly and can therefore result in very different calculated residual stresses. Experiments were conducted on cast stress lattices utilizing incremental hole drilling to measure strains. To calculate the residual stresses, global material parameters and standard evaluation procedures in accordance to ASTM E837 were used. Results show that the method is questionable for grey cast iron but can be used for ductile iron. Lack of material properties knowledged are suggested to be the main obstacle for residual stress evaluations on grey cast iron as the accuracy of the method decreases as hole depth approaches 1 mm.

Introduction

Cast irons are widely used in for example heavy duty diesel engines. The material allows for complex components to be cast to near-net-shapes without extensive post machining. A complex shape tends to result in different cooling rates over the cast component. These differences often results in pores at thermal centres and residual stresses from the thermal gradients during cooling. Different thicknesses of the component will result in thermal gradients that lead to residual stresses. Quantification of casting induced residual stresses is therefore important. Tensile residual stresses are detrimental and promote fatigue crack initiation and propagation whereas compressive residual stresses are beneficial for the fatigue strength. Critical load bearing positions on the component could rupture prematurely if the stresses are detrimental. It is therefore important for the industry to have a fast and reliable residual stress measurement method at hand.

Hole drilling and X-ray diffraction for residual stress measurements are common and widely used on a regular basis in industry today. These two techniques are mainly being used on steels, aluminium, titanium and nickel-base materials but also on some cast iron [1,11]. Incremental hole drilling (IHD) is a fast method for stress measurements and allows for collection of data from the first 1 - 2 millimetres below the surface. It is often described as semi-destructive testing and sometimes as non-destructive testing since the hole dimensions are small compared to the component. With IHD it is possible to measure in-plane non-uniform stresses on a macroscopic

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level. The method is based on strain relaxation as the hole is drilled. Changes in strain are measured by strain gauges attached to the surface. IHD works by drilling the hole in several small steps (increments) and between each step the relaxed strains are recorded. Strains are converted into stresses via one of the available mathematical methods such as Integral method, Kockelmann and Power series. Whilst main part of the published articles concerns the residual stresses from shot peening, welding or machining of the above mentioned material groups, very little has been done on cast iron [7]. There exists a lack of knowledge on how good IHD is for accurate stress measurements on cast iron. Therefore, this study has focused on IHD stress measurement on cast stress lattices in two different classes of cast iron: grey cast iron (GJL) and ductile iron (GJS). With the simple geometry of the cast stress lattice, the residual stresses can be simulated and thought be possible to verified by IHD.

Material and experimental procedure

Stress lattice were cast in grey cast iron class GJL-300 and ductile iron class GJS-500. Thickness were 25 mm, width of side bar were 12 mm, width of middle bar were 68 mm, distance between the bars were 35 mm and the overall length were 295 mm, see Fig 1a). The free graphite in GJL is in the shape of flakes, see Fig. 1b), and GJS as nodules. Young's modulus for GJL and GJS were set to 116 GPa and 185 GPa respectively, whereas the Poisson's ratio were set to 0.3 for both materials. For easier application of strain gauges the surface were machined on a small section across the width of the lattice, as visible in Fig. 1a). Depth of the machining was 600 - 700 µm.

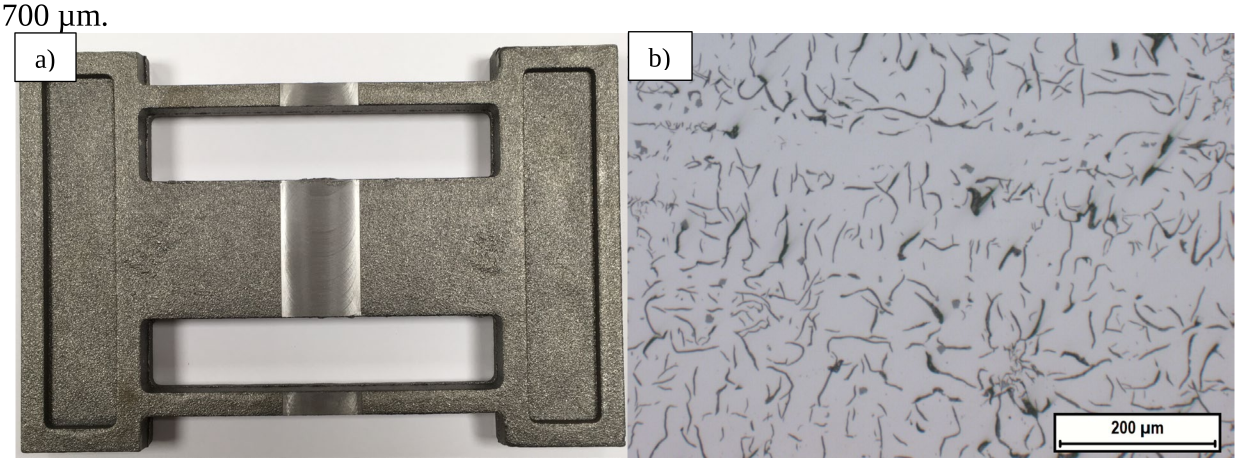

Figure 1: Stress lattice with the machined surface (a) and microstructural image of GJL from centre of the side bar showing type A and type E [12] graphite (b).

Hole drilling equipment used was Restan MTS-3000 from SINT Technology, having a high speed drilling of 350,000 - 400,000 rpm and 1.8 mm diameter inverted cone drill. It is a fully automatic process to ensure good repeatability and is compliant to ASTM E837-13. The method used is based on incremental hole drilling, meaning that the hole is being drilled step by step and between each step the relaxed strains are measured. Increments in steps of 180 µm were used, based on data given by Stefanescu *et al* [13]. With IHD it is possible to achieve good accuracy of the measured stresses [14,15] and therefore thought to be good for investigating cast iron. One hole drilled on GJS was conducted with 90 µm step size. Hole depth were 1.26 mm resulting in z/D = 0.494. Measurements were conducted on one stress lattice of either material. One hole were drilled on each side bar on both lattices and two holes in the middle bar on GJL and one hole on the middle bar on GJS.

Rosette strain gauges from HBM with three strain gauges oriented at 45° to each other having a gauge length of 1.5 mm and a rosette diameter of 5.1 mm were used.

Results

Measured stress distribution in GJL in the thicker middle bar and the thinner side bars overlap each other as illustrated in Fig. 2. Minimum stresses were found closest to the machined surface; -225 MPa for the middle bar and -285 MPa on the side bar. Maximum stresses were found to be 100 MPa for the middle bar and 50 MPa for the side bar located at the bottom position of the drilled hole. Around 700 µm depth all curves kinked and then continued rising.

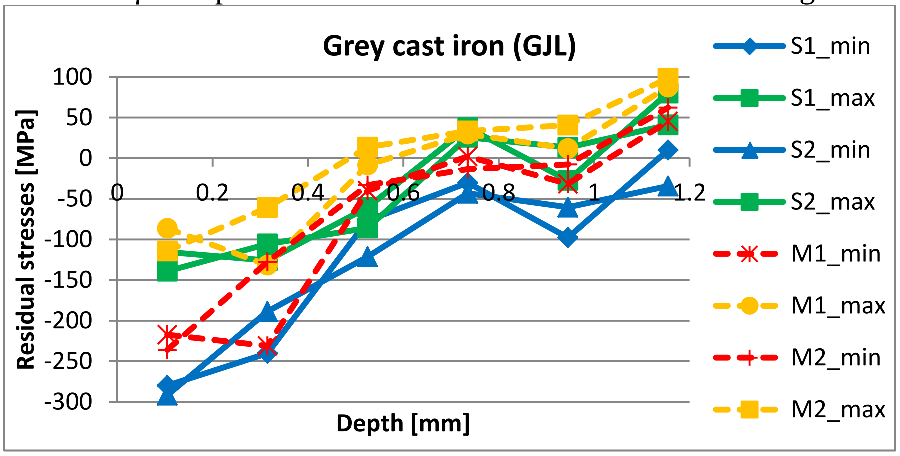

Figure 2: Residual stress distribution in as-cast stress lattice of grey cast iron. S1 and S2 are notations for drilled hole number 1 and 2 in the side bar and M1 and M2 are notations for hole 1 and 2 in the middle bar.

For spheroidal graphite iron the minimum stresses in the side bars were always lower than the middle bar as shown in Fig. 3. For the side bar, there is a trend of increased compressive stresses with depth from -100 MPa at the surface to -250 MPa at 1 mm depth. Maximum stresses are more or less always on the compression side with a few data points between 25 - 45 MPa at 700 µm to 1 mm depth.

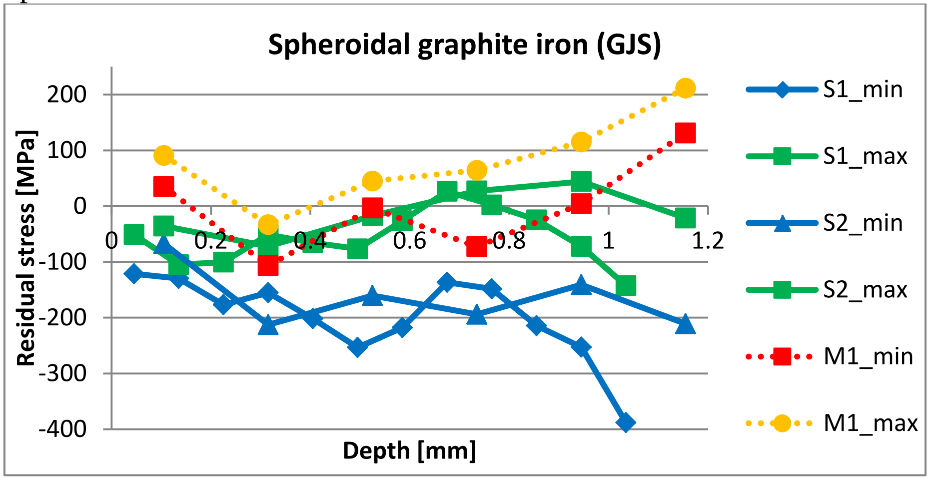

Figure 3: Residual stress distribution for spheroidal graphite iron. S1 and S2 refers to hole number 1 and 2 in the side bar and M1 refers to hole number 1 in the middle bar.

In the middle bar, the minimum stresses distribution shows a concave upward curve with tensile stresses at the surface followed by a decrease in stresses to -100 MPa before changing direction and reaching tensile stresses of 130 MPa. Same features can be said about the maximum stresses, with 100 MPa at the surface followed by its lowest value of -35 MPa at 300 µm and reaching it highest value above 200 MPa at full depth.

Discussion

When the stress lattices are cast, the side bars will solidify and cool down before the middle bar which has more material. When the middle bar solidify and cool down it want to contract but is hindered by the already solidified side bars. There will be compressive residual stresses in the side bars and tensile residual stress in the middle bar. Direction of the stresses will be along the bar axis. From simulation on GJL [16], the residual stress in the side bars should be around -190 MPa and in the middle bar around 95 MPa. For GJL this is not seen with IHD, no significant differences in residual stresses can be observed. Possible reasons for this could be machining induced plasticity, casting skin or variation in microstructure. One measurement was conducted directly on the as-cast surface on the middle bar after gentle polishing, to smoothen out the roughest patches. This measurement showed the same result as previously measurements and therefore the observed compressive stresses are not just from machining. GJL exhibit a non-linear elastic behaviour and is brittle. Graphite's loadbearing capacity in tension is low and basal planes start to slip below 30 MPa tensile load [17]. The graphite tip acts as stress raises making them perfect points for crack initiation. In compression the graphite supports the matrix and is loadbearing, resulting in a strongly anisotropic stress-strain curve between tension and compression [18]. Stress evaluations of IHD data on GJL material are complex due to its anisotropic load responds. Global parameters derived from tensile testing might not be enough for proper stress calculation and evaluation. Local variations in microstructure are a part of cast iron nature, providing some of its unique properties. Variations in graphite morphology are often seen because of different cooling rates and chemical variations. Microstructure investigation of the side bar revealed type D and type E graphite with some rosettes (type B) and no type A graphite as seen in Fig. 4. Microstructural study conducted prior to this investigation provided somewhat false conceptions regarding the actual graphite morphology in the investigated area. To the authors' best knowledge, no investigations have been conducted about local responses to these kinds of graphite morphologies. GJL matrix consists of different amounts of ferrite/pearlite, which also could lead to misinterpretations of the stresses if local variations are present [19,20]. If the matrix just underneath the attached strain gauges is pearlitic and almost fully ferritic after a few hundredth microns, then it is easy to suspect that material behaviour differs. However, the matrix of the investigated GJL was fully pearlitic and thus not being a concern of irregular loading responds between grains. It is a complex microstructure with different behaviour when investigated over different length scales. Therefore, several holes should be drilled and the results compared, as well as microstructural investigations. Better knowledge from thorough investigations are needed to understand the complex GJL material propertied before adequate stress evaluations of GJL using IHD are really feasible.

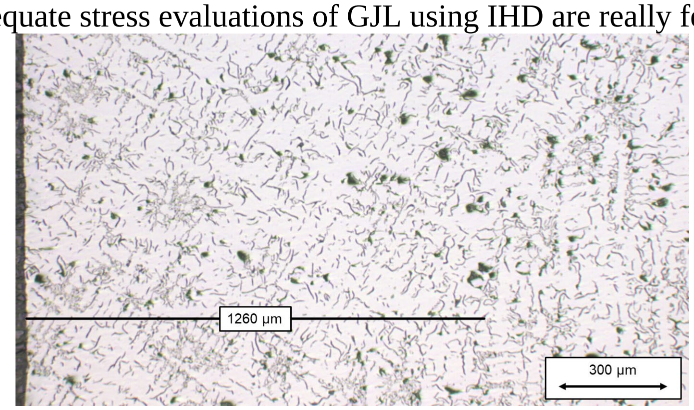

Figure 4: Typical microstructure in the side bar of GJL, left side is the machined surface.

Ductile iron load respond differs from grey cast iron. GJS and construction steel have a close resemblance in stress-strain curves with a clear linear part followed by plastic deformation and

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finally fracture. IHD was developed as a method to measure residual stresses in steels. And since GJS is somewhat similar to steel in its load respond, the IHD should result in plausible and realistic residual stress values for our GJS stress lattice and also seen in our investigation.

General recommendation for IHD measurement state that the measured stresses should be less than 80% of materials yield strength. This recommendation is cleared for GJS but not for GJL. Trying to meet this recommendation for GJL is difficult since the materials non-linear elastic behaviour turns the concept of yield strength to a fundamental issue to deal with for the scientific community. IHD stress calculations assume homogeneous material and material properties, which is not the nature of cast iron and especially GJL and this material seems to be too far away in its properties allowing for good stress measurements utilizing IHD. ASTM E837-13 also specifies that the maximum eccentricity error is 0.02 mm which was found to be difficult to fulfil for GJL, but not for GJS.

Measuring depth in [7] reveals the same tendency as seen in this work that stress evaluations beyond 700 µm depth isn´t really feasible for cast iron, not even GJS. The method as such is physically limited by Saint-Venant principle, meaning that the surface strain response to stresses quickly becomes insensitive and result in larger uncertainties with depth. For cast iron the total measuring depth suggested by the authors is z/D = 0.3. Residual stress measurements utilizing IHD on GJL should be done with extreme care and thorough analysis of the results are required for best possible outcome.

Other stress measuring techniques should preferably be conducted parallel to verify the IHD such as electronic speckle pattern interferometry or X-ray diffraction since these techniques captures the local mechanical responds better[21,22].

Conclusions

Feasibility of incremental hole drilling as a residual stress measurement technique on cast iron is still not clearly answered. Stress lattices, cast in grey cast iron and ductile graphite iron, were investigated and the following conclusions could be made:

- Stress measurements on GJS using IHD can be done and returns plausible residual stress values.
- IHD method seems to deteriorate beyond z/D = 0.3 depth.
- IHD for stress measurement on GJL gives questionable results.
- More investigation on material behaviour at different length scales are needed.

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