Fatigue strength of shot peened compacted graphite iron

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Abstract

This paper investigates the influence of shot peening on the fatigue strength of a compacted graphite iron (CGI) in two different surface conditions, namely as cast with casting skin and after machining to remove the casting skin. Four combinations of shot peening intensity level (0.07 and 0.1 mmA) and degree of coverage (80% and 120%) were applied. The results have shown that the shot peening has resulted in an increase in bending fatigue endurance limit of 8% to 23% for the CGI with casting skin and of 9% to 17% for the CGI with a machined surface. For both surface conditions, shot peening with the lower intensity but higher coverage or the higher intensity but lower coverage are more effective than the process using the lower intensity and coverage or the higher intensity and coverage. In total, a 49% increase in bending endurance limit has been achieved by combining machining and shot peening with 0.07 mmA and 120% coverage.

Key word Compacted graphite iron, shot peening, fatigue, residual stress.

Introduction

Cast irons are a rather inexpensive option when producing components with complex geometries, e.g. cylinder heads in heavy duty diesel engines. The component can be cast in a sand mould to nearly final dimensions thus minimizing the need for extensive post-machining. Because of the low strength graphite and casting defects, cast iron components often show relatively low mechanical properties such as static tensile strength and fatigue resistance. To meet the increasing demands of higher engine output power, lower emissions and better fuel economy, there is a strong industrial interest in increasing the fatigue strength of cast irons.

It is well known that compressive residual stresses located at the component surface and subsurface are beneficial for fatigue strength. A commonly used process to induce beneficial compressive residual stresses on metallic materials is shot peening. Accompanying with the treatment is also strain hardening, alteration of surface geometry and microstructural changes in a surface layer, which can be important for the fatigue life of the peened component. Shot peening as a topic has been studied for several decades now, and it has been proven to markedly increase the fatigue strength of, e.g., steel and aluminium once proper parameters have been adopted. However, shot peening or the effect of residual stresses on the fatigue strength of cast irons has not been studied extensively. Nonetheless, the limited publications on ductile irons [1-3], nodular cast irons [3,4] and austempered irons [5] do reveal a positive effect of shot peening.

The current work investigates the effect of applying shot peening on the fatigue performance of compacted graphite iron (CGI). Two surface conditions, one as cast with a casting skin and the other machined, were tested. For industrial practice, the peening effect is often controlled by varying the peening intensity level, which depends on the velocity as well as the size and hardness of the shots, and the degree of coverage which is a function of peening time. In the current study, four processes from different combinations of two intensity levels and two degrees of coverage were applied. The results have shown that all of them affect positively the bending fatigue strength.

Experimental details

The compacted graphite iron used in the current study has a pearlitic matrix with a small amount of ferrite and dominantly vermicular graphite. The nominal composition and mechanical properties, including the yielding stress Rp0.2 and tensile strength Rm, are given in Tables 1 and 2, respectively.

Table 1. Nominal chemical composition of the CGI

	C	Si	Mn	P	S	Cu	Cr	Mo	Fe
CGI	3.8	2.0	0.20	Max 0.05	0.01	0.90	0.02	0.005	Bal.

Table 2 Nominal mechanical properties (tensile test)

Material	Young's modulus [GPa]	Rp0.2 [MPa]	Rm [MPa]	Elongation [%]	Matrix hardness [HV0.025]
CGI	140-150	280	400	>=1-3.5	296 ± 45

Fatigue specimens were cast as plates (~25kg each) from which 11 specimens per plate where machined. Prior to the machining, the plates were gently cleaned from sand using a DC756 Cordless 2-speed drill/driver from Dewalt. The driver was mounted with a soft steel-brush and only the first gear was used to minimize the effect on the surface and subsurface of the specimens. The specimens (Fig.1) were then cut from the plates with the following dimensions: D=35mm, d=15mm (machined), ~20mm (with casting skin), h=10mm (machined), ~15mm (with casting skin). All specimens had a length of 200mm. For the bending fatigue testing, a test rig constructed by Scania was used (Fig. 1). The specimens were fixed at the ends with a bending moment applied via exchangeable springs, allowing adjusting the applied load. The stress ratio was 0.1.

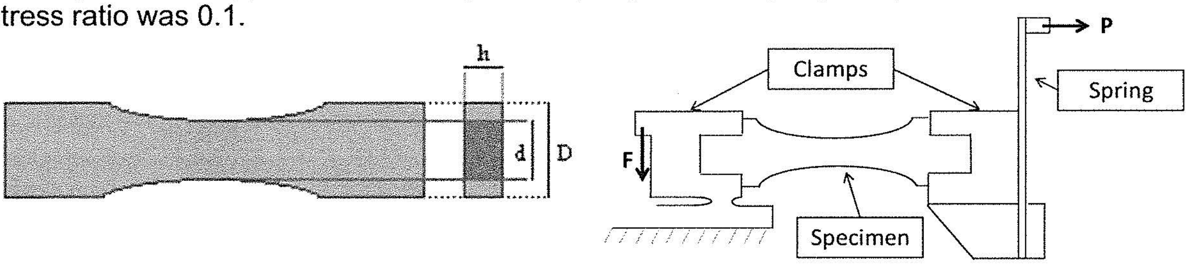

Fig.1 Left: A schematic picture of the specimens. Right: A principal sketch for the bending fatigue test: P corresponds to the applied force, resulting in a bending moment of the specimen, measured at F.

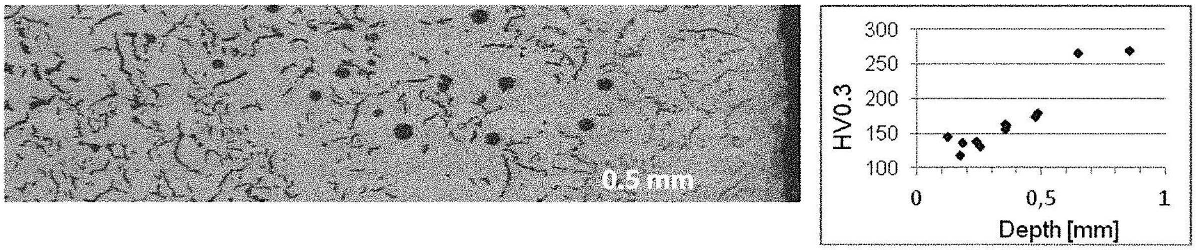

Fig. 2 Microstructure (left) and hardness profile (right) in the as cast CGI with a casting skin.

The microstructure of the as cast CGI is shown in Fig. 2. A surface layer, up to 0.5 mm thick, has a different microstructure than the bulk. The outer most surface layer, up to 50 μm thick, contains mainly Fe-oxides and some large particles of Si-oxides. Very fine flake inclusions rich in Si and C are observed right below the scale and the inclusions become larger further away from the surface. Microcracks or microcrack-like features (too fine to be visible in the figure) rich in Si and O are also common in the layer. As the hardness profile in Fig. 2 reveals, the matrix of the near surface layer, which is predominant in ferrite, is much softer than the essentially pearlitic matrix in the bulk. Cast steel shots S70H with a hardness of HRC 55-62 were used as shot peening medium. Our previous work has shown that shot peening with a high intensity may not improve fatigue strength [6]; therefore rather light peening intensities, namely 0.07 mmA and 0.1 mmA were chosen. Combining with coverage of 80% and 120%, four peening conditions were studied in the current work. Longitudinal cross-sections of selected specimens failed during fatigue were ground and polished for examination in a Hitachi FEG Scanning Electron Microscope (SEM) SU-70. Axial residual stresses in selected specimens, one as machined and the other machined, shot peened (0.07 mmA and 120% coverage) and then fatigue loaded (3×10^6 cycles at 135 MPa), were measured by X-ray diffraction (XRD) using Cr-$K\alpha$ radiation and ferrite-211 reflection. The $\sin^2\psi$ method with 13 measurement ψ-angles was used for deriving the stress value. The diffraction elastic constant, $\frac{1}{2}S_2$, needed for the stress calculation, is 5.8 $\times 10^{-6}$ MPa^{-1}. To obtain depth profiles, electrolytic polishing was used for material removal.

Experimental Results

A semi-logarithmic S-N curve was used to evaluate the results from the bending fatigue testing (i.e. to calculate a Wöhler curve), and a 3rd grade polynomial is fitted to the S-N data. The exponent m describes the slope of the S-N curve in the finite life area (below ~10^6 cycles) and the limit life level were kept free. The calculated confidence level, based on the method of least squares, was set to 80%. The obtained fatigue endurance limits are summarized in Table 3, while the fatigue data and derived S-N curves are plotted in Fig. 3-5. Fig. 3 compares the reference specimens with casting skin and the machined specimens. As is shown, removal of the casting skin by machining results in a better fatigue resistance: the whole S-N curve is shifted upwards with the fatigue endurance limit being increased by 27%. The machining also reduces scattering in the fatigue data, see the filled symbols in Fig. 3.

Table 3 Fatigue endurance limits for the different specimen conditions

Shot peening process		Non-shot peened	0.07 mmA 80%	0.07 mmA 120%	0.1 mmA 80%	0.1 mmA 120%
Casting skin	Fatigue strength [MPa]	113±16	122±12	138±17	139±7	133±8
	SP effect (%)	-	8%	22%	23%	17%
Machined	Fatigue strength [MPa]	144±11	161±6	169±8	165±10	157±7
	SP effect (%)	-	12%	17%	15%	9%
Casting skin	Machining + SP effect (%)	27%	42%	49%	46%	39%

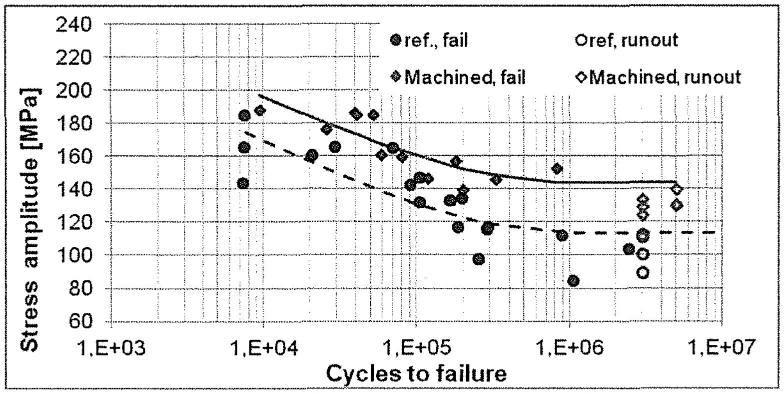

Fig. 3 Experimental data (symbols) and calculated S-N curves (lines) for the reference specimens with casting skin and the machined specimens.

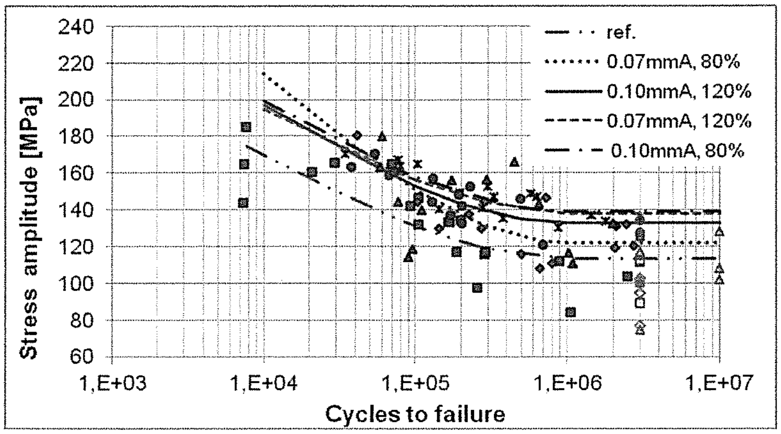

Fig. 4. S-N curves for specimens with casting skin in as cast (ref.) and shot-peened condition by different combination of peening intensity and coverage. Squares: reference; diamonds: 0.07mmA, 80%; triangles: 0.07mmA, 120%; asterisk/cross: 0.1mmA, 80%; circles: 0.1mmA, 120%. Filled symbols/asterisks represent failed specimens and open symbols/cross represent specimens that survives at least 3x10^6 loading cycles.

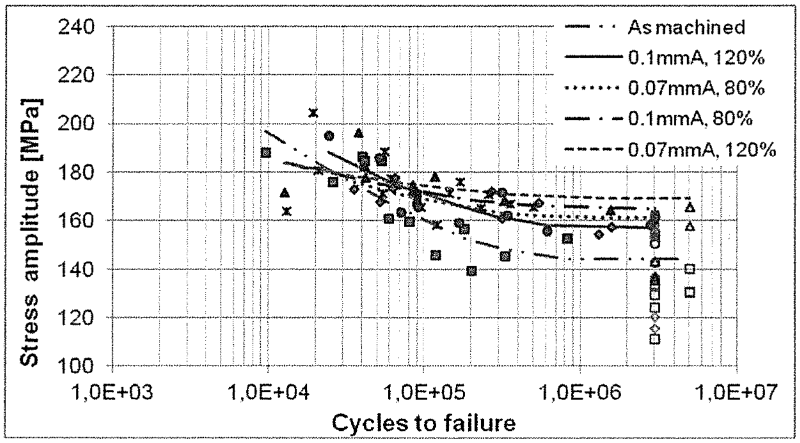

Fig. 5 S-N curves for machined specimens under different shot peening conditions. For the meaning of the symbols, see the caption for Fig. 4.

Fig. 4 and Table 3 show that all the shot peening processes employed lead to improved fatigue performance for the specimens with casting skin. Peening using the lower intensity (0.07mmA) but higher coverage (120%) or the higher intensity (0.1mmA) but lower coverage (80%) gives essentially the same and the largest increase in fatigue strength, over 20%, followed by peening using the higher intensity and coverage. The peening process with 0.07mmA intensity and 80% coverage has a small effect on the fatigue endurance limit, about 8%, but a stronger effect on the slope region. Both processes using the lower intensity show somewhat larger scattering in finite life region and the calculated fatigue strength.

The machined specimens also respond positively to the shot peening processes and show increased fatigue resistance. Like the specimens with casting skin, the combination of the lower intensity and higher coverage or higher intensity and lower coverage gives the largest increase, 17% and 15%, respectively. The other two combinations affect the fatigue limit similarly but the peening using the higher intensity and coverage has a stronger effect on the slope region. If both the effects of machined and shot peened are considered, 49% increase in the fatigue endurance limit is noted for the peening using 0.07 mmA intensity and 120% coverage and 46% for the peening using 0.1 mmA intensity and 80% coverage, larger than the other two peening processes.

Fig. 6 shows residual stresses along the axial direction of the machined specimen and the runout specimen in machining and shot-peening condition. Distribution of the diffraction peak width is also plotted to reveal plastic deformation gradient in the surface layer. The machining induces significant plastic deformation up to a depth of 25 µm, as revealed by the FWHM curve, but the compressive residual stress penetrates to a much larger depth. Shot peening increases largely the degree of plastic deformation in the surface and subsurface, though its influence on the compressive residual stresses seems to be much weaker. It is possible that the cyclic loading causes partial relaxation of the shot peening induced residual stresses. The low compressive stresses, about 50 MPa, at larger depths could be microstreses originating from thermal mismatch between the ferrite and cementite.

The SEM observation on the longitudinal cross-sections of selected specimens does not reveal obvious fatigue damage. Microcracks or crack-like features are common in the casting skin of abnormal microstructure for all conditions, including the as cast and untested specimen.

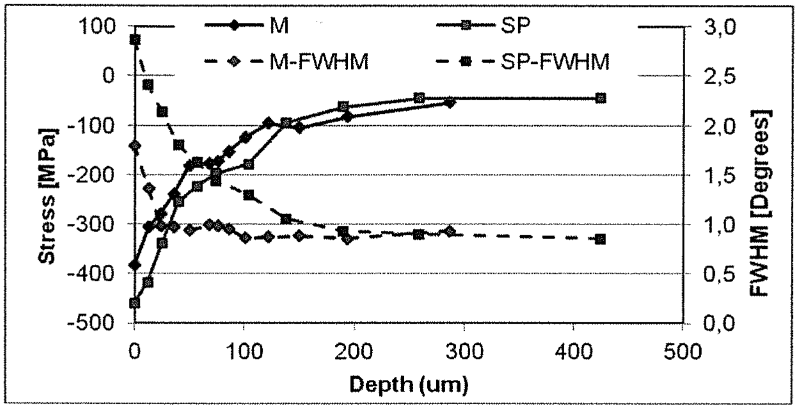

Fig. 6 Axial residual stresses and peak width. M: as machined; SP: runout specimen in machining + shot peening condition.

Discussions and Conclusions

It is known that cast irons with casting skin often show lower fatigue strength than the machined counterparts [7]. EDS analysis in the current work indicates that the crack-like features are often microcracks related to silicon oxides. Microhardness testing in these regions does not seem to induce further cracking, revealing ductile ferritic grains with low hardness. The lower fatigue resistance with larger scattering observed for the as cast specimens can be explained by a rougher surface [7] and a softer surface layer, both of which are absent in the machined specimens. In addition, the machining induced strain hardening and compressive stresses (Fig. 6) further increase the difference.

Shot peening of the machined specimens increases the degree and extension of strain hardening (Fig. 6). The compressive stresses, although measured on a specimen that may have experienced stress relaxation, are still larger in the surface layer than the machined specimen without being cyclically loaded. Both the increased strain hardening and compressive stresses further enhance the fatigue resistance of the machined specimens. For the slope regions where the specimens are subjected to a higher loading stress, stress relaxation may occur, leading to a diminishing effect of shot peening.

It was not possible to measure residual stresses in the specimens with casting skin as it was difficult to remove homogeneously the oxide scale by chemical or electrochemical method. However, higher hardness is detected in the casting skin after shot peening and the longitudinal cross-section displays fragmented oxide scale but otherwise intact cast skin. Therefore, the increased fatigue resistance can be ascribed to shot peening induced strain hardening and compressive residual stresses.

To optimize the shot peening process for best fatigue resistance is not a trivial task as the fatigue behaviour of the peened component depends on complex interactions between peening induced changes in the surface layer and the process of fatigue crack initiation and propagation [8]. For a given type of peening media, the peening process is often regulated through peening intensity and coverage. Increasing intensity and coverage may increase both the plastic deformation and compressive stresses in the peening affected layer but increasing the coverage over 100% seems to have much smaller effects [9]. Coverage less than 100%, e.g. 80%

used in the current work, means a less homogeneous plastic deformation in the peened surface. If strain hardening is supposed to be the dominant mechanism for increased fatigue strength, a lower affect would be observed for peening to 80% coverage as locations which were not peened and therefore remain soft can become crack initiation points. The observation that 0.1 mmA and 80% coverage gives essentially the same effect as 0.07 mmA and 120% may indicate that the induced compressive residual stresses are more important for the fatigue resistance of the shot peened CGI.

In summary, shot peening using rather low peening intensity, Almen A 0.07 or 0.1, and relatively low degree of coverage, 80% or 120%, improves the bending fatigue resistance of the CGI by introducing strain hardening and more importantly compressive stresses in a surface layer. Peening using 0.07 mmA but 120% coverage or 0.1 mmA but 80% coverage are most effective for both the as cast and machined conditions.

Acknowledgement

Financial supports from VINNOVA – Sweden's Innovation Agency through the program FFI - Strategic Vehicle Research and Innovation are greatly appreciated. Mrs Annethe Billenius is acknowledged for the XRD measurements and help with the metallographic examinations.

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