Shot peening effect on fatigue life of EN GJS 600-3 grade ductile iron wheel hubs

W Arshad¹,², H A Bilal², Z G Sun¹, W Shi¹ and A Godfrey³

¹Department of Mechanical Engineering, Tsinghua University, Beijing, China
²Govt. Swedish Pakistani College of Technology, Gujrat, Pakistan
³Laboratory of Advanced Materials (MoE), School of Materials Science and Engineering, Tsinghua University, Beijing, China

E-mail: huax18@mails.tsinghua.edu.cn

Abstract. Durability of wheel hubs is limited by their fatigue failure. Wheel hubs are mostly manufactured by casting process using ductile iron, and their fatigue strength can be improved by shot peening, which induces compressive stresses at their surfaces. In this study, fatigue life of wheel hubs manufactured from grade EN GJS 600-3 iron was studied. Shot-peened and untreated wheel hubs were subjected to fatigue test with the number of loading cycles up to 1 million. The test results showed that all untreated wheel hubs failed the test, while all shot-peened ones passed the 1 million cycle’s milestone. This study proved that fatigue life of wheel hubs manufactured from grade EN GJS 600-3 iron was improved almost by 100 percent via shot peening.

1. Introduction

External flaws are the integral part of a manufacturing process in a material and handling of that process is critical [1]. The fatigue life of materials is reduced by surface flaws [2]. The defects are generally characterized into the damaging defects, the non-damaging defects and by the magnitude of flaw in regard to fatigue strength [3]. The fatigue limit of the material is not reduced by non-damaging flaws. Shot peening is a very important technique to increase the fatigue limit of different materials [4] such as, aluminum alloys [5], steel [6], titanium alloys [7] and magnesium alloys [8]. Shot peening changes the surface properties of the material. Material shows some variations which are as follows: (i) residual stress distribution, (ii) surface profile [9]. Fortunately, shot peening is a useful method for maximizing the size of non-damaging flaw [10] and moreover it improves the fatigue strength of materials [11] like high-strength steels [12]. Ductile iron is a very famous materials which has a decent combination of design flexibility, low cost, toughness, good strength-to-weight ratio, and wear resistance [13]. Ductile iron has excellent castability, which gives production advantages. Though, the fatigue strength of ductile iron for dynamic load is not good. Experimentation is in process to increase the fatigue limit of ductile iron [14]. However, some experimental outcomes have been given on the austempered ductile iron [15] and the effect of shot peening is studied [16]. Shot peening involves blasting mechanism in which high velocity steel or glass balls are bombarded on the specimen surface. Shot peening puts the surface and a thin sub-surface layer of the targeted object in compression while there is tension on the inner side of the material [17]. Because of these compressive residual stresses the fatigue strength increases [18] and surface cracking is delayed [19]. Therefore, in this paper, the effect of shot peening on the fatigue strength of wheel hubs is studied to analyze its effect on EN-GJS 600-3 grade ductile iron samples.
2. Experimental

Samples were prepared through the casting process in green sand. As sand plays an important role in the sand casting process so different parameters should be in control for a sound casting. Results of different test which were used to analyze the sand are given in Table 1. The sand was tested by using methods of physical test for foundry sand IS 1918.

| Sand Test         | Value | Range    | Sand Test         | Value | Range    |
|------------------|-------|----------|------------------|-------|----------|
| Compactability   | 35%   | 30-40%   | Cope hardness    | 90 (B scale) | 85-95 (B scale) |
| Moisture         | 4.1%  | 3.0%-4.5%| Drag hardness    | 85 (B scale) | 85-95 (B scale) |
| Permeability     | 116   | 90 up    | Compression strength | 21.7N/cm² | 12-26 |
| Splitting strength | 4 N/cm² | 6-8     |                  |        |          |

Wheel hubs were manufactured by using ductile iron. High frequency induction furnace of 1.5 ton capacity was used. The melt was heated up to 1550°C and then tapped into 750 kg ladle which was preheated. Mg alloy in the form of FeSiMg was placed at the bottom of the ladle as nodulizer by using sandwiched method. FeSi was added into the stream of the melt for inoculation. First mold pouring temperature was 1410°C and last mold temperature was 1340°C. The average pouring time of each mold was 6.2 second. The molds were preheated up to 200°C. Core was placed in the drag while filter was placed inside the core to avoid the slag in the casting. Cope was carefully placed on the drag and melt was poured into the molds. Exactly 15 molds were prepared using the EN GJS 600-3 grade of ductile iron. The composition was checked via the spectrometer, which results are given in Table 2. There were no defects on the casting of the hub. The last poured hub was cut into eight equal parts, as shown in Figure 1.

| Element | Percentage | Element | Percentage | Element | Percentage | Element | Percentage |
|---------|------------|---------|------------|---------|------------|---------|------------|
| C%      | 3.77       | Mg%     | 0.036      | Cu%     | 0.279      | Mn %    | 0.3        |
| Si %    | 2.21       | S%      | 0.005      | Cr%     | 0.0127     | P%      | 0.0126     |

3. Results and Discussion

Each of the cut section out of eight is shown below in Figure 2 to observe the section view separately. Each section showed that there was no macro level visually observed porosity in each of the section and all the sections were perfectly sound. A sample for tensile testing was prepared from separately cast open mold. The samples were prepared by using standard DIN EN 1563. The drawing of separately cast mold is shown in Figure 3 and the dimensions are given in table 3. Tensile specimens were prepared by using ISO 6892-1 standard. The drawing of the specimen is given in Figure 4(a). The stain rate was set to be 0.002s⁻¹. The tensile test result of separately cast mold revealed yield strength of 426 N/mm² and ultimate tensile strength of 626 N/mm² with elongation of 13.9%. Four samples were prepared from the wheel hub to observe the tensile testing results from the casting. The tensile test specimens were extracted from the upper portion of the wheel hub as shown in Figure 2. The dimensions of the specimen prepared from the wheel hub are given in Figure 4(b) and the prepared samples are shown in figure 5. The mechanical properties, including the ultimate tensile strength (UTS), of cast samples are given in
table 4. The tensile test specimens prepared in a separately cast mold underwent the microporosity shrinkage due to mold design. However, the actual component design may have some porosity defects. Therefore, the specimen prepared from the actual component depicts real conditions and reveal lower strength due to microporosity shrinkage [20]. There is a linear relationship between tensile strength and the fatigue strength. Increase in tensile strength give rise to fatigue strength up to a certain level for ferrous materials [21]. The cross-section was subjected to Brinell (HB) hardness testing at the labelled spherical depressions indicated in Figure 6. The hardness results are given in table 5. The average hardness of wheel hub was 187 HB. The wheel hub generally exhibited consistent hardness values at different locations tested.

**Figure 2.** Wheel Hub sections to observe porosity.  
**Figure 3.** Separately Cast mold.

| Dimensions | Units (mm) |
|------------|------------|
| U          | 10         |
| V          | 100        |
| X          | 50         |
| Y          | 200        |
| Z          | 200        |

**Figure 4.** Separately cast tensile testing sample dimensions (a) Separately cast (b) within wheel hub.

Cut section was further divided into 5 sections (A, B, C, D, and E) to observe the microstructure as shown in Figure 6. All the sections have similar microstructure and no anomaly was observed. The microstructure of the hub from section A is shown in Figure 7. The micrographs ferrite, pearlite content and nodularity was determined by comparing with idealized micrographs. The microstructure of the wheel hub revealed that there is approximately 45% ferrite and 55% pearlite. The spherical nodularity is greater than 90 percent and difference of microstructure between different sections is quite negligible. There were no carbides (cementite) found in the microstructure.

Three of the wheel hubs were shot-peened to improve their fatigue life. The shot-peening parameters are given in Table 6. Shot peening was performed in two intervals. First of all, it was performed on the...
casting surface before machining. After turning operation, localized shot peening was performed on the upper surface of the hub before drilling operation. Figure 8 shows the difference between the untreated surface and shot-peened one. It can be observed from Figure 8 that shot-peened surface is smoother than the untreated one. This observation was further confirmed by profilometer results as shown in Figure 9. These results showed that cast/shot-peened sample has smooth surface as compared to cast surface. Similarly machined/shot-peened surface has a better surface finish, as compared to simply machined one. Wheel hubs with and without shot peening were subjected to fatigue testing. All samples were tested under the test procedure SAEJ1095. Fatigue test parameters are listed in Table 7. The fatigue test setup is shown in Figure 10 for a better visualization.

![Figure 5. Tensile samples prepared from wheel hub casting.](image)

![Figure 6. Hardness sample.](image)

**Table 4.** Tensile test results of samples taken from the wheel hub casting.

| Samples | UTS, MPa | Yield strength, MPa | Elongation, % |
|---------|----------|---------------------|---------------|
| 1       | 431      | 385                 | 3.6           |
| 2       | 446      | 395                 | 6.0           |
| 3       | 525      | 465                 | 6.0           |
| 4       | 546      | 480                 | 5.6           |

**Table 5.** Hardness Results.

| Hardness points | Hardness, HB |
|-----------------|--------------|
| A               | 194          |
| B               | 181          |
| C               | 181          |
| D               | 190          |
| E               | 190          |

![Figure 7. Microstructure of material grade EN GJS 600-3. Sample was etched in Nital 3% etchant (3% Nitric acid in ethanol).](image)

**Figure 7.** Microstructure of material grade EN GJS 600-3. Sample was etched in Nital 3% etchant (3% Nitric acid in ethanol).

**Figure 8.** a) Machined surface b) Machined/shot-peened surface.
Table 6. Shot-peening parameters.

| Parameter          | Value  |
|--------------------|--------|
| S330 shot ball size, mm | 0.8    |
| Pressure, bar       | 6      |
| Rotation speed, rpm  | 30     |
| Distance, mm        | 200    |
| Angle, degree       | 80     |
| Time (casting area), min | 30    |
| Time (machining area), min | 30 |

All the tests were conducted to achieve 1 million cycles over a given load. The wheel hubs without shot peening failed at much lower cycles during fatigue testing than the desired number of cycles. The result of the fatigue test results are given in Figure 11. The wheel hub completed 484,913 cycles and then failed due to crack propagation. At the final inspection, the wheel hub was dye checked for cracks as shown in figure 12. There were two cracks, which were found on the flange of wheel hub. Two more samples without shot peening were subjected to fatigue testing to achieve 1 million cycles, but both the samples failed at 484297 and 567392 cycles respectively. Similarly, three samples of wheel hubs with shot peening treatment were subjected to fatigue test under the SAE j1095 procedure. All the three samples passed the 1 million cycle’s milestone. The fatigue test graph is shown in Figure 13, which clearly shows that it has achieved the 1 million cycles at the given load.

![Figure 9. Surface roughness.](image1)

![Figure 10. Fatigue test setup.](image2)

![Figure 11. Fatigue test graph (without shot peening).](image3)

![Figure 12. Wheel hub sample (without shot peening) dye checked for cracks.](image4)
After successful fatigue tests of shot-peened wheel hubs, samples were dye checked as shown in Figure 14 which shows that there were no cracks on the surface of the wheel hub. The crack initiated from the surface of wheel hub (without shot peening) is shown Figure 15. All the wheel hubs with shot peening completed the 1 million cycles, while all wheel hubs without shot peening failed at much lower numbers of cycles, as shown in Figure 16. These results show that shot peening increased the fatigue life of wheel hub almost twice, as compared to untreated ones. Usually, a bone plate type sample is used for fatigue testing. For accurate results, fatigue testing needs to be performed on actual components. Fatigue test data to quantify the improvement in fatigue strength for wheel hubs made from material grade EN-GJS 600-3 after shot peening are not available elsewhere.

In shot peening compressive stresses are induced to improve subsurface characteristics which retards tiny cracks and introduce the work hardening of the surface [22]. Fatigue cracks mostly starts from the surface of the component, as the stresses due to provided loads such as torsion and bending are high at the surface as compared to the inside of the material [23]. The fatigue strength of the sub-surface material is also on higher side (almost 1.4 times than that of the surface) [24]. Shot peening moves the fatigue crack zone to the subsurface area due to the residual compressive stresses. This is advantageous as the fatigue strength is higher beneath the surface. The residual compressive stress and the hardened layer make crack formation not to occur from the surface, but still micro-cracks develop at sub-surface [25]. In addition, the surfaces are exposed to machining and imperfections can act as stress raisers. These imperfections induce unfavourable residual stresses that can affect the fatigue strength adversely. Shot peening induces residual stresses and cold work. Each response parameter is critical for fatigue strength. The surface residual compressive stress should be kept high for minimum fatigue crack growth. Residual compressive stresses on the surface prevents the crack growth. Due to strain hardening on the surface as a result of shot peening retards the propagation of cracks. Plastic deformation and the residual compressive stress provides a corresponding crack closure stress that reduces the driving force for crack propagation. The residual stress level and maximum residual stress reduces after applying fatigue load.
Surface roughness quickens the crack initiation while cold working retards the crack initiation. Shot peening also improved the surface finish of wheel hubs. Surface finish has extensive effect on fatigue strength. Better surface finish leads to higher values of fatigue strength [27]. In the present study, the reason for fatigue life improvement by shot peening can be attributed to retardation of micro crack growth [23], residual compressive stresses [22], strain hardening of the surface layer [27] and better surface finish owing to the positive effect on fatigue life.

4. Conclusion
Ductile iron wheel hub samples were subjected to fatigue testing where the aim was to reach 1 million cycles without failure. The samples without shot peening failed and could not reach the targeted number of cycles, while all of the shot-peened samples withstood the desired number of cycles without failure. The fatigue life improvement due to shot peening was attributed to residual compressive stresses, and better surface finish. So it is stated from the above results that shot peening can improve the fatigue strength (by almost 100%) of the wheel hubs manufactured from EN-GJS 600-3.

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